# Impact of Link Failures on an Optical Packet-Switched Manhattan Street Network 

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Abstract - In this paper we examine the problem of resilience in a Clockwork Routing scheme employed in a Manhattan Street Network (MSN) network architecture. The MSN has been proposed as a promising candidate for high-speed optical packet-switched applications. In this paper, we study the impact of single physical link or node failures on the self-routing topology and the effects on the routing behaviour of the MSN are discussed.

## 1. Introduction

The Manhattan Street Network (MSN) is a type of self-routing network topology proposed for local and metropolitan area network applications. Originally proposed by Maxemchuk in 1985 [1], the MSN is a two-connected regular grid network topology with alternating circulatory arcs. The wrap-around links logically place the two-dimensional grid on the surface of a torus (Figure 1). The MSN has been considered as a logical topology for lightwave networks because of its simple routing and control mechanisms.


Figure 1: Depiction of a $4 \times 4$ Manhattan Street Network
The MSN is a time-slotted system and each node comprises of a $2 \times 2$ switch. Every node can receive at most two packets in one time -slot (one on each input stream) and packets are switched from each of the incoming links to outgoing links at every time-slot. The MSN has been introduced as a topology for lightwave networks and several routing schemes have been proposed in the literature $\llbracket, 2 \rrbracket$ using deflection routing and store-and-forward techniques. Recently, the Clockwork Routing scheme has been proposed as a candidate for implementing optical packet-switched networks. This scheme offers a number of attractive features: no contention, no re-sequencing at destination nodes, no need for optical domain buffering and exhibits a throughput that is comparable to conventional store-and-forward packet switching [3, 4].

However, a major drawback to the applicability of the Clockwork Routing scheme is its fragility to network failures, as this requires the entire topology to remain operable. The logical operation of the Clockwork Routing can be represented as a collection of independent rings or Logical Loops (LLs) [5]. A single LL is highlighted in Fig. 2(a). In this paper we examine the impact of a single physical link/node failure for an embedding of the Manhattan Street Network using Clockwork Routing (MSNCR ) onto an arbitrary physical topology. In general, the failure of a single link or node has an undesirable network-wide impact, i.e., a physical failure may cascade into a set of multiple LL failures (Fig. 2(b)).


Figure 2: (a) Depiction of a logical loop (dotted line).

(b) Multiple LLs bundled into one fibre.

## 2. Parameters of Interest

We identify several parameters are of interest and these are listed in Table 1. Computed values are given for both a $4 \times 4$ and a $6 \times 6$ MSN and general expressions are given for an NxN MSN.

| MSN-CR Parameter | NxN MSN | 4X4 MSN | 6x6 MSN |
| :--- | :---: | :---: | :---: |
| Node pairs | $\mathrm{N}^{2}\left(\mathrm{~N}^{2}-1\right)$ | 240 | 1260 |
| Logical loops (LLs) | $2 \mathrm{~N}^{3}$ | 128 | 432 |
| Node pairs in one LL | $4 \mathrm{~N}^{2}-6 \mathrm{~N}+2$ | 42 | 110 |
| Logical links per LL | 2 N | 8 | 12 |
| LLs incident on each logical link | N | 4 | 6 |
| Time slots | $\mathrm{T}_{0}, \mathrm{~T}_{1}, . . \mathrm{T}_{\mathrm{N}-1}$ | 4 | 6 |
| Node pair losses per LL | $\mathrm{N}(\mathrm{N}-1) / 2+(\mathrm{N}-1)^{2}$ | 15 | 40 |

Table 1: MSN-CR parameters of interest

## 3. Quantifying the impact of a logical link failure in the MSN-CR

Prior to investigating the impact of a physical link failure on the MSN-CR virtual topology, we examine the impact of logical link and loop failures for the example of a $4 \times 4$ MSN. When a logical link between source node 1 and destination node 2 fails, four LLs 1-4 (attached to time-slots 0-3) are impacted (Figure 3). Each LL is composed of eight logical links and these are listed in Table 2.

| Logical Loop | Logical Link Sequence |
| :--- | :--- |
| LL1/Time slot 0 | $(1,2),(2,3),(3,4),(4,1),(1,5),(5,9),(9,13),(13,1)$ |
| LL2/Time-slot 1 | $(1,2),(2,3),(3,4),(4,16),(16,12),(12,8),(8,4),(4,1)$ |
| LL3/Time-slot 2 | $(1,2),(2,3),(3,7),(7,11),(11,15),(15,7),(3,4),(4,1)$ |
| LL4/Time-slot 3 | $(1,2),(2,14),(14,10),(10,6),(6,2),(2,3),(3,4),(4,1)$ |

Table 2: Logical links enumerated for each logical loop/time-slot
Thus, a single link failure in the MSN-CR will affect 4 LLs thus triggering a total loss of 32 logical links and 60 node pairs. The total logical link and node pair losses can be computed using equations Eq. 1 and Eq. 2 respectively.

Total Logical Link Losses $=($ LLs incident on each logical link) $x($ Logical links per LL) Eq. 1 Total Node Pair Losses = (LLs incident on each logical link) $x$ (Node pair losses per LL) Eq. 2


B - Bar C - Cross
Figure 3: Logical loops 1-4 respectively attached to time-slots 0-3

## 4. Methodology

This paper studies an embedding of the MSN-CR onto the NFSNET physical topology (Figure 4 depicts such an embedding). An embedding maps each logical link in the MSN onto one or more links in the physical topology. Near-optimal embedding techniques have been proposed in the literature [6, 7] and we employ heuristic techniques based on Hill Climbing and Simulated Annealing to solve the embedding problem. However, in this paper our emphasis is on the resilience of the MSN-CR and we assess the impact of single physical link or node failures given any embedding solution. In this study, we have identified that the embedding cost that minimises the number of node pair losses is the maximum lightpath load per fibre.


Figure 4: An example of an embedded MSN-CR onto NFSNET physical topology

## 5. Results

Figure 5 shows the relation between the number of embedding iterations and the lightpath load per fibre. The results shows that the maximum lightpath load per fibre can be minimised to 3 and 4 lightpaths and the total number of lightpaths can be reduced to 51 and 52 using Simulated Annealing and Hill Climbing techniques, respectively. Table 3 shows results pertaining to the Simulated Annealing simulation and results are shown for the number of lightpath loads per fibre, the node pair losses, the number of LLs, and the number of LL failures for each physical fibre. It is evident that any physical link failure cascades to an unacceptable amount of logical failures.

The results show that the highest $L L$ loss is $9.375 \%$, which occurs upon failure of physical links $(2,14)$, $(5,7)$ or $(10,12)$. To illustrate this impact we consider physical failure of link $(2,14)$ as shown in Figure 6(a). In this example there are 3 lightpaths (representing 3 logical links) traversing physical link $(2,14)$, i.e. logical links $(4,16),(9,13)$, and $(15,3)$ are impacted by the failure of this link as shown in Figure 6(b). This cascades into a total loss of 12 LLs in the MSN-CR, i.e. almost the entire MSN is impacted.


Figure 5: Plot of the Number of Lightpath Load per Fibre vs. Embedding Iteration

## 5. Conclusion

This paper has outlined the resilience problem of a MSN-CR topology embedded onto an arbitrary physical lightwave network. We have demonstrated the fragility of the Clockwork Routing scheme to single link failures and for a particular embedding of the MSN-CR we have shown that a single link failure can disrupt the entire network. We have also shown that the number of logical link failures is sensitive to the embedding.

## 6. Future Work

Future work will examine embedding heuristics that minimises the loss of node pairs and loops in the higher layer and path restoration techniques will be investigated.

| Physical <br> Node Pairs | No. Of <br> Logical Link | Node Pair | \% Pair | Nosses | Losses | Nof |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Nogical Link | Losses | Losses |  |  |  |
| $(0,1)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(0,2)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(1,3)$ | 1 | 15 | 6.25 | 1 | 4 | 3.125 |
| $(1,4)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(1,9)$ | 3 | 45 | 18.75 | 3 | 12 | 9.375 |
| $(2,3)$ | 3 | 45 | 18.75 | 3 | 8 | 6.25 |
| $(2,7)$ | 3 | 45 | 18.75 | 3 | 8 | 6.25 |
| $(2,14)$ | 3 | 45 | 18.75 | 3 | 12 | 9.375 |
| $(4,5)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(5,6)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(5,7)$ | 3 | 45 | 18.75 | 3 | 12 | 9.375 |
| $(5,11)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(6,10)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(7,8)$ | 3 | 45 | 18.75 | 3 | 8 | 6.25 |
| $(8,9)$ | 1 | 15 | 6.25 | 1 | 4 | 3.125 |
| $(9,10)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(10,12)$ | 3 | 45 | 18.75 | 3 | 12 | 9.375 |
| $(11,12)$ | 2 | 30 | 12.5 | 2 | 4 | 3.125 |
| $(11,13)$ | 2 | 30 | 12.5 | 2 | 4 | 3.125 |
| $(12,14)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(12.15)$ | 3 | 45 | 18.75 | 3 | 8 | 6.25 |
| $(13,14)$ | 2 | 30 | 12.5 | 2 | 8 | 6.25 |
| $(13,15)$ | 1 | 15 | 6.25 | 1 | 4 | 3.125 |

Table 3: Failure Analysis


Figure 6: (a) Depicted link failure $(2,14)$ and (b) its impact (failure of three logical links).

## 7. References

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