Availability Analysis for Elastic Optical Networks with Multi-path Virtual Concatenation Technique

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Abstract— Due to high spectrum efficiency and flexibility in bandwidth allocation, elastic optical networks receive extensive research interest in recent years. Availability is one of the most important Service Level Agreement (SLA) metrics in telecommunication networks. In the paper, we apply the sub-band Virtual Concatenation (VCAT) technique to enhance the availability of elastic optical networks. Our study shows that the VCAT technique can greatly enhance the availability of the elastic optical networks, different spectrum distributions of sub-bands (i.e., numbers of frequency slots (FSs)) on multiple paths of a VCAT light path service can greatly impact the network availability, and a higher availability can be expected for a smaller VCAT sub-band granularity.

1. INTRODUCTION

Because of the unique merits, such as high spectrum efficiency and flexibility in bandwidth allocation, elastic optical networks receive extensive research interest in recent years. Availability is one of the most important SLA metrics in telecommunication networks. Different from reliability that is concerned about how likely a system will operate for a certain time period without a service-affecting failure occurring, availability considers external repair and maintenance to recover from failures, which is concerned about the state probability of finding a system in an operating state at any time when we want its service [1]. For the availability analyses of optical transport networks, the majority of existing studies focus on Wavelength Division Multiplexing (WDM) optical networks [2]. Different network protection techniques have been applied to enhance service availability in WDM networks [3–5]. However, to the best of our knowledge, there is still no study dedicated to the availability analysis for the elastic optical networks.

On the other hand, in the traditional Optical Transport Network (OTN), VCAT is an important technique to flexibly split the bandwidth of a complete service connection into multiple Virtual Containers (VCs) in the time domain, transport the VCs via different end-to-end paths, and finally recombine them at the receiver [6]. The VCAT technique can well balance the traffic load in the network, thereby significantly improving network capacity utilization. For the elastic optical network, it is also possible to extend this concatenation technique in the spectrum domain to split a complete light path into multiple sub-bands, transport the sub-bands via different paths, and finally recombine them at the receiver [7]. This technique is called *sub-band VCAT* or *spectrum split*. The distribution of sub-bands on multiple different paths enables partial bandwidth to survive when a network incurs failure(s). Thus, the sub-band VCAT technique is expected to enhance light path service availability for the elastic optical network.

This paper evaluates the benefit of applying the sub-band VCAT technique in enhancing the availability of the elastic optical networks. We develop analytical models specifically for two cases, i.e., (1) a single link-based node pair, between which multiple parallel links connect, and (2) a general mesh network, in which multiple disjoint end-to-end paths are employed for each node pair to provision light path services through the VCAT technique, and a network-wide average end-to-end connection availability is calculated. We assume that all the remaining capacity is available when one or multiple paths of a multi-path VCAT service are affected. Our study indicates that the sub-band VCAT technique can greatly enhance the availability of the elastic optical networks, and different distributions of sub-bands (i.e., numbers of FSs) on different paths of a VCAT light path service can greatly impact the network availability. For the single-link case, under the assumption of an equal link length of all the parallel links, an even distribution of FSs on the links can achieve the highest availability. For the network case, the distribution of FSs that ensures the highest network availability depends on the network topology. Also, a higher availability can be expected for a smaller VCAT sub-band granularity.

The rest of the paper is organized as follows. In Section 2, we give the assumption and a new availability definition, on which our analyses are based. In Section 3, we evaluate the availabilities for two cases, i.e., a single link-based node pair and a general mesh network containing multiple end-to-end node pairs. We conclude the paper in Section 4.

2. ASSUMPTIONS AND NEW AVAILABILITY FORMULA

Network outages can be caused by both fiber cable cuts and invalidity of network node equipment (i.e., node failures). However, according to the statistics, the main reason for network failures is due to fiber cable cuts [2]. Thus, in this study we mainly focus on link failures (arising from fiber cable cuts) when analyzing network availability. We have the following four key assumptions for the analyses, including (1) network links are either working or in the outage state, (2) links fail independently, (3) both the in-service time and repair time of fiber cables follow independent memoryless processes with a constant mean, and (4) the repair rate is much greater than the failure rate [2].

The most widely known equation for the availability of a link is $A_l = MTTF/(MTTF+MTTR*l)$, where A_l is the link availability, $MTTF$ is the Mean Time To Failure of the link per km, and $MTTR$ is the Mean Time To Repair, l is the length of the link. FIT is the Failure In Time, which is a standard unit for measuring or specifying failure rates, and 1 FIT means 1 failure in 10^9 hours. Without losing generality, in this paper, we assume that $MTTF = 1\,\text{km}/(200*\text{FIT})$, and $MTTR = 6\,\text{hours}$ [2].

Because a network as a whole is neither entirely available nor entirely failed, it is meaningless to directly estimate "network availability." Rather, it is more meaningful and practical to characterize the link availability, path availability, and then based on these availabilities we can analys is a network-wide average end-to-end connection availability. If a path contains M continuous links, the path availability is $A_p = \prod_{i=1}^{M} A_l^i$, which requires all the contained links are available and where A_l^i is the availability of the ith link on the path as defined before.

In the elastic optical network, the sub-band VCAT technique enables a connection (with multiple sub-bands on different paths) to survive partial bandwidth when a network incurs failure(s). Considering the partial available bandwidth with the VCAT technique, we define a new link availability as follows:

$$Ae_l = (MTTF*B_t + MTTR*l*B_r*A_r)/(MTTF+MTTR*l)*B_t \tag{1}$$

where B_t denotes the total bandwidth of the VCAT connection between a pair of source and destination nodes, B_r denotes the remaining bandwidth when link failure(s) occur, and A_r is the availability of the remaining capacity B_r. The numerator in the equation finds the total available bandwidth, in which the first part corresponds to the bandwidth when there is no failure and the second part corresponds to the remaining bandwidth when link failure(s) occur. The denominator in the equation finds total bandwidth if there is no link failure in the period of $MTTF+MTTR*l$.

3. AVAILABILITY ANALYSES

This section analyzes the availabilities for two cases: a single link-based node pair connected with multiple parallel links and a general mesh network with multiple end-to-end VCAT light path connections.

3.1. A Single Link-based Node Pair Connected by Multiple Parallel Links

3.1.1. Two Parallel Links

We first consider the case of two parallel links. Fig. 1 shows a situation where a single node pair is connected by two parallel links. Assume that B_1 is the bandwidth of first link, B_2 is the bandwidth of second link, and B_t is the total bandwidth between the two nodes, where $B_t = B_1 + B_2$, and their units are FS. When the first link fails, B_2 is the remaining capacity between the node pair. Similarly, when the second link fails, B_1 is the remaining capacity between the node pair.

Based on Equation (1), the availability for the first and second links with the VCAT technique can be calculated as (2) and (3).

$$\begin{aligned} Ae_l^1 &= \left(MTTF*B_t+MTTR*l_1*A_l^2*B_2\right)/(MTTF+MTTR*l_1)*B_t \\ &\approx (MTTF*B_t+MTTR*l_1*B_2)/(MTTF+MTTR*l_1)*B_t \end{aligned} \tag{2}$$

$$\begin{aligned} Ae_l^2 &= \left(MTTF*B_t+MTTR*l_2*A_l^1*B_1\right)/(MTTF+MTTR*l_2)*B_t \\ &\approx (MTTF*B_t+MTTR*l_2*B_1)/(MTTF+MTTR*l_2)*B_t \end{aligned} \tag{3}$$

where l_1 and l_2 are the physical lengths of the two links, respectively, and A_l^1 and A_l^2 are the availabilities of the two links based on the original availability definition, respectively, which are typically very close to 1.

For the two end nodes, the VCAT connection availability can be formulated as (4), and the unavailability of the connection is formulated as (5).

$$Ae_c = \left(Ae_l^1 * B_1 + Ae_l^2 * B_2\right) / B_t \tag{4}$$

$$U_c = 1 - A_c \tag{5}$$

Given the physical lengths of the two links, Equation (4) is solely dependent on the two variables B_1 and B_2, which means that different distributions of sub-bands (i.e., numbers of FSs) on the two links can impact the connection availability. To achieve a maximal availability, we need to find the combination of B_1 and B_2 that can make the first derivative of (4) equal zero. We find that when B_1 satisfies Equation (6), we can achieve maximal connection availability.

$$B_1 = \frac{\left(MTTF * MTTR * l_2 + 2 * MTTR^2 * l_1 * l_2\right) * B_t}{\left(MTTF * MTTR * (l_1 + l_2) + 2 * MTTR^2 * l_1 * l_2\right)} \tag{6}$$

Based on (6), we consider all the combinations of B_1 and B_2 to find maximal connection availabilities for various link length situations. Assume that the length of the first link equals 1,000 km and the total bandwidth of the connection is 10 FSs (i.e., $B_1 + B_2 = 10$ FSs), we find different connection availabilities considering different lengths of the second link (Len2) and combinations of B_1 and B_2. Fig. 2 shows the connection unavailabilities for these different situations, in which each curve corresponds to a certain length of the second link and the horizontal axis shows variable numbers of FSs on the first link. We can see that for each length of the second link, there exists minimal connection unavailability for a certain combination of B_1 and B_2. For example, when the length of the second link is 500 km, the minimal connection unavailability occurs when the combination of B_1 and B_2 is (3, 7) FSs, and similarly, when the length of the second link is the same as the first link, i.e., 1,000 km, the minimal connection unavailability occurs when the combination of B_1 and B_2 is (5, 5) FSs, which means that specially for the equal link case, we should evenly split the total bandwidth onto the two links so as to achieve a maximal connection availability. Based on the above results, we can conclude that when the length of second link is longer, the maximal achievable availability is lower and the first link should be distributed with more FSs so as to achieve higher availability. We also analyze how the range of length of the second link affect the combinations of B_1 and B_2 when achieving minimal unavailability. The results are shown in Table 1. We can see that the results are in line with those in Fig. 2, i.e., when the length of second link is longer, the first link should be distributed with more FSs to achieve the minimal connection unavailability.

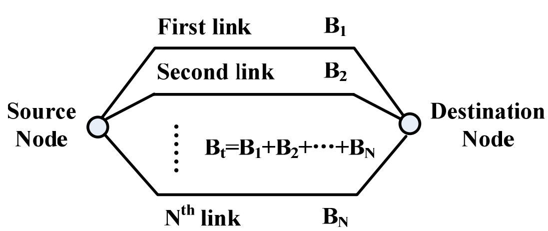

Figure 1: A simple demonstration for two nodes.

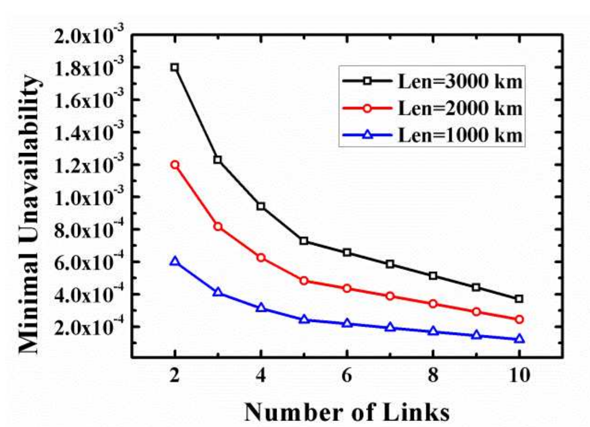

Figure 2: Connection unavailability for Len2.

3.1.2. Multiple Parallel Links

We next consider a single link-based node pair with multiple (more than two) parallel links as shown in Fig. 3. Considering the remaining capacity when a link failure occurs, the link availability is given by Equation (7), and the connection availability is given by Equation (8).

$$Ae_l^k = \left(MTTF * B_t + MTTR * l_k * \sum\nolimits_{i=1, i \neq k}^{N} A_l^i * B_i\right) \Big/ (MTTF + MTTR * l_k) * B_t \quad (7)$$

$$Ae_c = \sum\nolimits_{i=1}^{N} \left(Ae_l^k * B_i\right) \Big/ B_t \quad (8)$$

where l_i denotes the length of the ith link, N denotes the number of parallel links between the two nodes, A_l^i is the availability of the ith link *not* considering the remain capacity, which can be calculated by $A_l^i = MTTF/(MTTF + MTTR{*}l_i)$, B_t denotes the total number of FSs, and B_i denotes the number of FSs on the ith link.

Because the connection availability is dependent on the number of parallel links and the distribution of FSs, given the set and parameters of N, $MTTR$, $MTTF$, l_i, A_l^i, and B_t as defined before, we develop an optimization model to find the maximal connection availability as follows:

Variables: Ae_l^i is the new availability of the ith link, which is calculated by (7). B_i is the number of FSs on the ith link.

Objective: $Maximize Ae_c = \sum_{i=1}^{N} \left(Ae_l^i * B_i\right) \Big/ B_t$. (i.e., maximize the average connection availability under different link failure situations)

Constraints: $\sum_{i=1}^{N} B_i = B_t$. (i.e., the sum of FSs distributed on all the parallel links equals to the total number of FSs of the connection).

Table 1: FS combinations of different ranges of Len2for minimal unavailability.

	Range of Len2 (km)		Optimal FSs of 1st link	Optimal FSs of 2nd link
	Min	Max		
1	0	53	0	10
2	53	176	1	9
3	176	333	2	8
4	333	538	3	7
5	538	818	4	6
6	818	1222	5	5
7	1222	1856	6	4
8	1856	3007	7	3
9	3007	5699	8	2
10	5699	19419	9	1
11	19419	Infinity	10	0

Table 2: Minimal unavailability under different numbers of links.

Num Links	Minmal Unavailability	Optimal FSs distribution on different links									
		1	2	3	4	5	6	7	8	9	10
2	0.000599999	5	5								
3	0.000408459	3	4	3							
4	0.000312689	3	3	2	2						
5	0.000240862	2	2	2	2	2					
6	0.000216919	2	2	2	2	1	1				
7	0.000192977	2	2	1	1	2	1	1			
8	0.000169034	2	1	1	1	1	1	2			
9	0.000145092	1	1	1	2	1	1	1	1	1	
10	0.000121149	1	1	1	1	1	1	1	1	1	1

If the lengths of the links are different, the objective formula has quadratic components. In order to linearize the model, we assume that the lengths of all the links are the same, i.e., $l_1 = l_2 = \ldots = l_N = l$, and thus $A_l^1 = A_l^2 = \ldots = A_l^N = A$. We evaluate the availability of the connection between the two nodes with different parallel links. Assume that the lengths of all links are 1,000 km, $MTTR = 6$ hours, $MTTF = 5{\times}10^6$ hours*km, and $B_t = 10$ FSs, Table 2 shows the minimal unavailability to be achieved under different numbers of links and corresponding FSs distributions.

We observe that an even distribution of FSs on different links can achieve a maximal availability. In addition, we can see that a higher availability can be expected for a smaller VCAT sub-band granularity. The result is reasonable because when the length of all links are the same, and the number of links is fixed, an even distribution of FSs can make the probability of failed FSs minimal, and therefore the connection availability maximized. Also, with the increase of the number of parallel links, there are fewer FSs affected when a single link failure occurred, and thus the probability of failed FSs is lower.

Figure 4 shows the minimal unavailability of the connection between two nodes under different numbers of parallel links. Each curve corresponds to a certain link length. We observe that the shorter length of a link shows a lower unavailability. In addition, we see that a lower unavailability can be expected for a smaller VCAT sub-band granularity.

3.2. General Mesh Network

In this section, we estimate the availability of service connections for a general mesh network under the sub-band VCAT technique. We first consider a single end-to-end node pair, which is then used

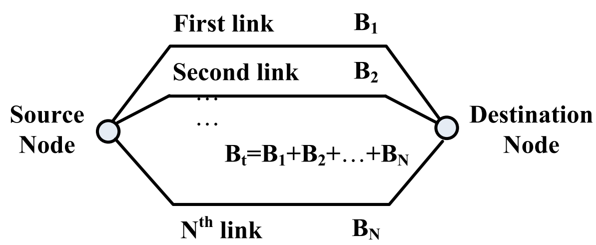

Figure 3: A single node pair connected with multiple parallel links.

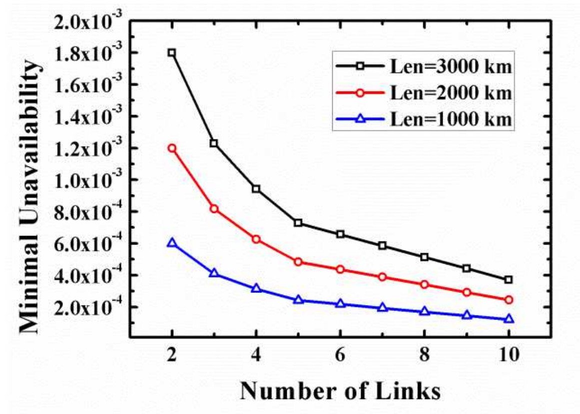

Figure 4: Minimal unavailability under different numbers of parallel links.

to calculate the availability for all the node pairs in a network. We average the availabilities of end-to-end light paths for all the node pairs to obtain average network-wide connection availability.

Figure 5 shows a single node pair connected by multiple disjoint end-to-end paths. Considering the remaining capacity upon a link failure, the availability of the ith link on the kth path is given by Equation (9), where l_{ki} denotes the length of the ith link on the kth path, N denotes the number paths between the source and destination nodes. A_p^j is the availability of the jth path not considering the remaining capacity, calculated as $A_p^j = \prod_{i=1}^{M_l^j} A_l^{ji}$, where A_l^{ji} is the availability of the ith link on the jth path not considering the remain capacity, i.e., $A_l^{ji} = MTTF/(MTTF+MTTR{*}l_{ji})$, and M_l^j denotes the number links that the jth path traverses. The path availability is given by Equation (10), and the overall connection availability is given by Equation (11), where B_t is the total number of FSs, and B_k denotes the number FSs allocated on the kth path. The enhanced availability considers all the single-link failure situations and averages path availability considering the remaining capacity.

$$Ae_l^{ki} = \left(MTTF * B_t + MTTR * l_{ki} * \sum_{j=1, j\neq k}^{N} A_p^j * B_j\right) \Big/ (MTTF + MTTR * l_{ki}) * B_t \quad (9)$$

$$Ae_p^k = \prod\nolimits_{i=1}^{M_l^k} Ae_l^{ki} \quad (10)$$

$$Ae_c = \sum\nolimits_{k=1}^{N} \left(Ae_p^k{*}B_k\right) \Big/ B_t \quad (11)$$

As shown in Fig. 5, assume that there are two paths between a pair of nodes. The first path traverses two links with lengths of 500 km and 1,000 km, respectively, and the second path traverses three links with lengths of 500 km, 1,000 km, and 2,000 km, respectively. We can employ the availability calculation equations from (9) to (11) to estimate the end-to-end connection availability. The results are shown in Fig. 6, in which unavailability is considered. We compare the connection unavailability for the cases of single path and two paths. We see that the minimal connection unavailability of the two-path case with VCAT is lower than that of any single path case without VCAT. This is because the VCAT technique can integrate the sub-bands on multiple paths to make up an end-to-end light path service, which can ensure some bandwidth to survive when incurring a failure and therefore greatly enhance the connection bandwidth availability.

We apply the above end-to-end connection availability analysis approach to all the node pairs in a mesh network and calculate a network-wide average end-to-end service availability. We use a modified Dijkstra's algorithm to find two link-disjoint shortest routes between each node pair. For performance comparison, we evaluate the minimal unavailability of the first shortest path without VCAT, the second shortest path without VCAT, and the two shortest paths with VCAT. Two test networks including the n6s8 and SmallNet networks are considered for such an evaluation. Figs. 7

and 8 show the results of n6s8 and SmallNet, respectively. Because the remaining capacity can be considered available when one (or multiple) paths of a multi-path VCAT service is affected, it is easy to understand that the connection unavailability of two paths with VCAT is lower than that of any single path without VCAT.

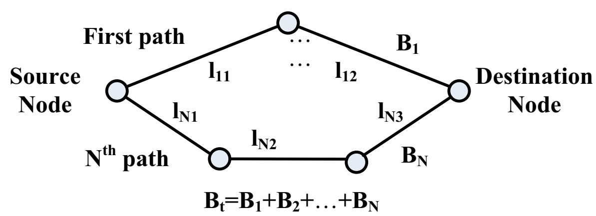

Figure 5: A single node pair connected withmultiple paths.

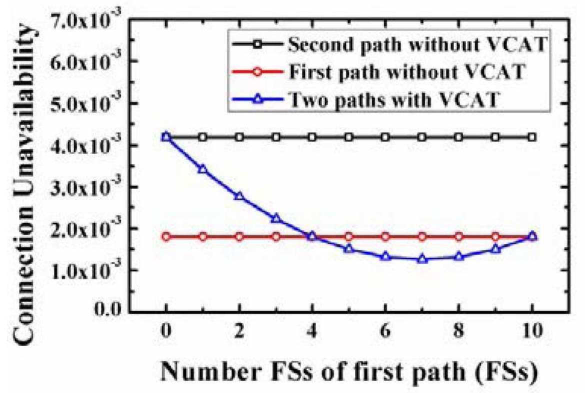

Figure 6: Unavailability comparison for a node pair.

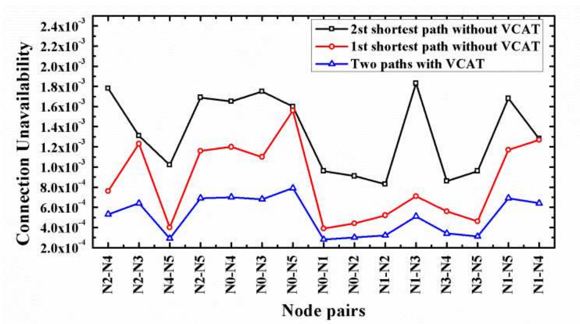

Figure 7: Unavailability comparison for the n6s8 network.

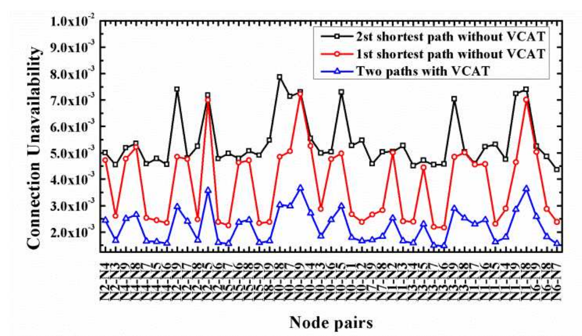

Figure 8: Unavailability comparison for the SmallNet network.

4. CONCLUSIONS

This paper evaluates the benefit of applying the sub-band VCAT technique in enhancing the availability of the elastic optical network. We made theoretical analyses for the situations of a single link-based node pair and a general mesh network. Because the distribution of FSs on different links between a link-based node pair can affect the connection availability, we also developed an optimization model to maximize the connection availability for the node pair. We found that under the assumption that the lengths of all links are the same, an even distribution of FSs on different links can achieve the highest availability, and a higher availability can be achieved for a smaller VCAT sub-band granularity. For the case of end-to-end paths in a mesh network, the sub-band VCAT technique can also greatly enhance the availability of service connections. It is also found that the distribution of FSs that can achieve the highest availability depends on the network topology, and a higher availability can also be expected for a smaller VCAT sub-band granularity.

ACKNOWLEDGMENT

This work was jointly supported by the National 863 Project of China (2012AA011302), National Natural Science Foundation of China (NSFC) (61172057, 61322109), Research Fund for the Doctoral Program of Higher Education of China (20113201110005), and Natural Science Foundation of Jiangsu Province (BK2012179, BK20130003).

REFERENCES

1. Billinton, R. and R. N. Allan, *Reliability Evaluation of Engineering Systems*, 2nd Edition, Plenum Press, 1992.
2. Grover, W. D., *Mesh-based Survivable Networks: Options and Strategies for Optical, MPLS, SONET, and ATM Networking*, Prentice Hall Professional, 2004.
3. Clouqueur, M. and W. D. Grover, "Availability analysis of span restorable mesh networks," *IEEE Journal on Selected Areas in Communications*, Vol. 20, No. 4, 810–821, May 2002.
4. Arci, D., D. Petecchi, G. Maier, et al., "Availability models for protection techniques in WDM networks," *Proc. DRCN*, 2003.
5. Grover, W. D., "High availability path design in ring-based optical availability," *IEEE/ACM Transactions on Networks*, Vol. 7, No. 1, 558–574, Aug. 1999.
6. Choy, L., "Virtual concatenation tutorial: Enhancing SONET/SDH networks for data transport," *Journal of Optical Networking*, Vol. 1, No. 1, 18–29, Jan. 2002.
7. Shen, G., A. Cai, and L. Peng, "Benefits of sub-band Virtual Concatenation (VCAT) in CO-OFDM optical networks," *Proc. ICTON*, 2012.