

On the Spectrum-Efficiency of Transparent Optical Transport Network Design with Variable-Rate Forward Error Correction Codes

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Abstract—We discuss the flexible rate optical transmission enabled by forward error correction (FEC) codes adjustment. The adaptation of FEC codes to given transmission condition gives rise to trade-off between transmission rate and optical reach. In this paper, that compromise is addressed from network planning standpoint. A static transparent network planning taking into account that rate-reach trade-off is formulated. A case study is solved in realistic NSF network with a comparison between mixed line rate (MLR) (10/40/100 Gbps) and flexible rate (FlexRate) by FEC variation (10-100 Gbps with a step of 10 Gbps). The result shows that the maximum link load could be reduced up to ~60% in FlexRate compared with MLR and the reduction becomes evident at high traffic load. Moreover, thanks to finer rate adaptation, the FlexRate could support an amount of traffic around three times higher than MLR.

Index Terms—Flexible Optical Network, Forward Error Correction, Network Optimization, Elastic Transponder, Fiber-Optic Communication.

I. INTRODUCTION

The increasing penetration of rich-bandwidth services such as video on demand, high definition TV and cloud computing are pushing urgent needs for improvements in optical transport network (OTN). Increasing efficiency therefore becomes key requirement for such improvements. From architectural standpoint, transparent network is a promising one with characteristic of all-optical transmission from source to destination, and therefore avoid unnecessary optical-electrical-optical conversion (O-E-O) at intermediate nodes. Moreover, transparent architecture also brings additional benefits of bit-rate, protocol and signal format transparency [1]. However, the absence of O-E-O processing at intermediate nodes poses challenges in design issues when accumulated physical impairments from source to destination might degrade the quality of optical signal. Since the currently deployed network is based on fixed transmission technologies, the design therefore must be carried out from the worst case in term of transmission performance in order to guarantee that all optical paths can work in a robust way. This inherently causes common constraint of transmission rate (channel capacity) for the whole network while in practice, several optical channels might have a higher

attainable capacity due to certain redundant transmission margins at receiving ends [2].

Given this limitation, future solutions must be able to adaptively utilize resources to each connection path, instead of fixed design based on the worst case. Mixed line rate system is a step toward that end. By utilizing a set of discrete transponders at different capacities (e.g., 10/40/100 Gbps), the spectrum efficiency could be improved. However, it is still relied on fixed transponders which just provide very coarse adaptation of transmission rate. Additionally, the operation and management of different transponder types might give rise to number of issues [2]. Thanks to recent advances in digital signal processing at both transmitter and receiver, elastic optical transponder is coming into availability (e.g., [2], [3], [4]). Elastic transponder enables the optimization of channel capacity, transmission reach, spectral occupancy on a channel-by-channel basis by configuring transmission parameters such as modulation format, baud-rates, FEC codes, etc. according to connection path condition. The utilization of such transponder potentially results in operation expenses decrease by having fewer transponder type and more importantly, increase efficiency of network resources [2]. The rise of flex-grid concept enabled by introduction of elastic transponder and flex-grid ROADM is perhaps the most significant topic in optical networking community recently [5]. While the potential benefits has been justified, it should be seen as not a near future solution since the deployment requires significant replacement of network infrastructure (e.g., new flex-grid ROADM) as well as complicating network management [3].

Instead, the solution that both fits within currently deployed infrastructure (i.e., fixed-grid) and provides certain degree of adaptation should be sought for. However, there are still few works addressing this alternative. For example, in [3], the use of elastic transponder with modulation format adaptation is mentioned and justified from the cost perspectives. Another degree of freedom, FEC code is also a potential technique for adapting channel capacity to transmission conditions. Recent advances in FEC techniques allows a wide-range of transmission rate variation and expect to opens up new possibilities for improving network efficiency. Inspired by recent result

in [6], this paper will focus on the spectrum-efficiency of flexible rate enabled by FEC adjustment in network planning. In section II, we briefly describe how FEC variation is realized and its impact to network planning. Section III formulates the static transparent network planning taking into account flexible rate transmission by variable-rate FEC. An illustrative result on NSF network topology is given in section IV with a comparison between MLR and FlexRate. Finally, conclusions with forward lookings are presented in section V.

II. RATE-ADAPTIVE TRANSMISSION BY FEC ADJUSTMENT

Figure 1 shows the simplified OTN frame that basically includes two parts: information area and attached FEC parity area [7]. Depending on the specific channel condition, FEC redundancy is adjusted to guarantee robust transmission. The first option for such adjustment could be realized by varying the frame length while keeping the information area constant. Such option ensures the fixed rate of client-side and change overall optical transmission rate (network-side). Since the maximum rate from network side is restricted by hardware design of optical transponder [7], the FEC adjustment is limited by that factor. In contrast, the second option, without need of varying the frame length, adjust the FEC redundancy by flexibly using part of information area for transmitting parity bits. This approach keeps the net bit-rate constant while the information rate (channel capacity) is adapted to channel condition. For example, for long distance, channel capacity could be traded for increasing of FEC overhead for robust transmission. The latter approach is favored in [7], [6] since it can overcome hardware restriction and be compatible with fixed grid system. In this paper, we just focus on second option, that is, the channel capacity is adapted according to transmission requirement without changing the net bit-rate (i.e., same modulation format, same channel spacing).

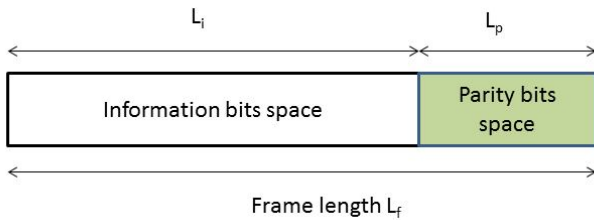


Fig. 1: Simplified OTN frame

As an illustration, we introduce here the result from [6], which proposed rate-adaptive transmission scheme employing variable-rate FEC codes with a fixed signal constellation and a fixed symbol rate. As the transmission conditions changes (i.e., signal to noise (SNR) changes), the FEC codes is adjusted to maximize the information rate while keeping net bit-rate constant. Such adjustment was realized by means of puncturing or shortening a single code, called a mother code, to generate derived codes of various rates. In particular, PM-QPSK transponder with symbol rate of 29.4152 Gbaud/s

working in nominal 50-GHz channel spacing yields peak information rate of 100 Gbps at 2000 km and decrease around ~40% for each additional 1000 km up to ~5000 km at zero SNR margin [6].

From networking planning standpoint, such flexible rate transmission is modeled as a network supporting different channel capacities with their corresponding reaches.

III. MATHEMATICAL FORMULATION

This part formulates the static network planning process with flexible rate enabled by varying FEC. Such scheme offers a set of transmission rate options depending on reach requirement. We adopt here the common objective in network planning, that is, to minimize maximum link load. It should be noticed that the overall rate is kept constant while the information bit-rate could be changed leading to diverse transmission rate options.

A. Input Parameters

- $G(V, E)$: Physical topology of the network with V nodes and E links.
- D : Set of request, indexed by d . Each request d requires t_d traffic in $Gbps$.
- $R = \{r_1, r_2, \dots, r_k\}$: Set of available rates in $Gbps$. Each rate r_i is associated with maximum optical reach l_{r_i} .
- W : Set of wavelengths supported on a link, indexed by w .
- P_d : Set of candidate paths for demand d , computed by k-shortest paths algorithm.
- $P = \cup_{d \in D} P_d$: Set of all paths, indexed by p .
- $r_p \in R$: the highest rate that can work transparently along path p .
- P_e : Set of paths that go through link e

B. Variables

- x_p : Boolean variable indicates the selection of path p (x_p equals to 1 if path p is selected and equals to 0 otherwise)
- y_p^w : Boolean variable indicates the wavelength usage of path p (y_p^w equals to 1 if path p is selected and uses wavelength w and equals to 0 either if it is not selected or not use the wavelength w)
- $u \in \mathbb{Z}^+$: positive integer number indicates the maximum link load (i.e., in term of number of wavelength channels)

C. ILP Formulation

$$\text{Minimize } u \quad (1)$$

subject to the following constraints:

$$\sum_{p \in P_d} x_p = 1 \quad \forall d \in D \quad (2)$$

$$\sum_{w \in W} y_p^w = x_p \cdot \lceil \frac{t_d}{r_p} \rceil \quad \forall d \in D, p \in P_d \quad (3)$$

$$\sum_{p \in P_e} y_p^w \leq 1 \quad \forall w \in W, \forall e \in E \quad (4)$$

$$\sum_{p \in P_e} \sum_{w \in W} y_p^w \leq |W| \quad \forall e \in E \quad (5)$$

$$\sum_{p \in P_e} \sum_{w \in W} y_p^w \leq u \quad \forall e \in E \quad (6)$$

The objective function in Eqn. 1 aims at minimizing maximum link load (MLL) measured by number of wavelength channels. Equation 2 imposes the single-path routing for all demands (i.e., lightpath connections of one demand must be routed on the same route). Satisfaction of traffic demand is taken care by Eqn. 3. It is noted that for each candidate path of demand, the highest line rate is selected to carry the traffic. Equation 4 enforces the no wavelength collision on each link (i.e., each wavelength is used at most one times on a single-fiber link). Equation 5 set the capacity limitation of each link and Eqn. 6 gives the definition of cost function.

IV. ILLUSTRATIVE RESULTS AND DISCUSSION

We use NSF network topology (14 nodes, 21 bi-directional links) with link distances in km as in Fig.2. The number of wavelength on each link direction is assumed to be 80, corresponding to 4 THz overall spectrum. A comparison is drawn between MLR (10/40/100 Gbps) and FlexRate (10-100 Gbps with a step of 10 Gbps). The reach-rate model for FlexRate system enabled by FEC adjustment is adopted from [6], which has detail calculation in Table I. According to [6], the rate is decreased by $\sim 40\%$ for every 1000 km. We assume that decrease is valid up to ~ 5000 km, and with distance longer than that, the transponder works at 10 Gbps information rate. The reach for MLR is equivalent to FlexRate's reach at their common rates. We also limit k-shortest path algorithm to 3, corresponding to longest path ~ 6000 km in order to have reasonable assumption of transparent operation for 10 Gbps. The traffic is bi-directional, all-to-all uniform starting from 10 Gbps with an increment of 10 Gbps (i.e., traffic profile i corresponds to $i \times 10$ Gbps traffic between nodes pairs). The proposed ILP formulation is implemented in Matlab and solved with the solver IBM ILOG CPLEX v.12.4, academic version. Optimal results are obtained for different scenarios and collectively presented in Fig. 3, 4, 5.

Figure 3 presents the optimized MLL value versus traffic profiles for MLR and FlexRate design at different values of k (i.e., $k=1, 2, 3$). It can be seen that for three values of k , a similar general trend is observed, that is, as traffic grows, the absolute gap between MLR and FlexRate also increase, indicating the more spectrum-efficiency of FlexRate over MLR at high traffic load. It is noticed that for $k=1$ in Fig. 3(a), the MLL for MLR quickly approaches link capacity bound, and thus, MLR could just support up to traffic profile 6, with MLL reaching 73. By introducing more candidate paths, the MLL is generally decreased for both MLR and FlexRate as in Fig. 3(b) and Fig. 3(c). This makes MLR to be able to support up to traffic profile 9 with MLL of 76 and 75 at $k=2, 3$ respectively while MLL for FlexRate is just 28 and 26, showing a significant reduction.

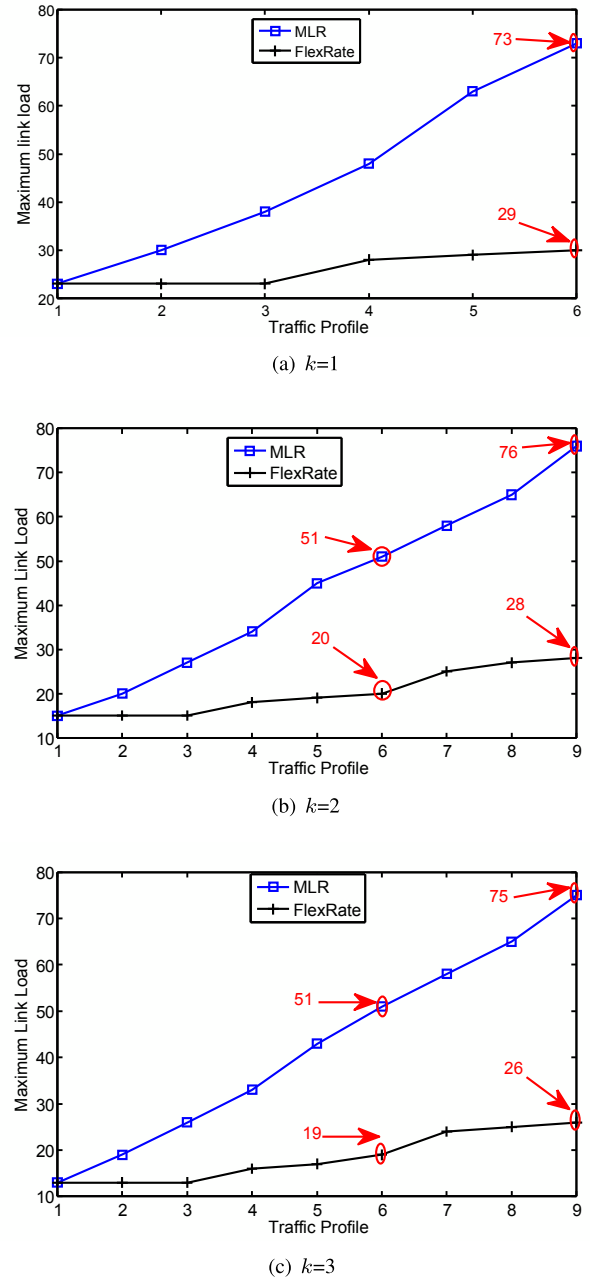


Fig. 3: Maximum link load comparison at different k

In term of percentage, Fig. 4 details how much gain that FlexRate achieves over MLR. It is shown that there is a steep gain increase up to traffic profile 3, followed by a mild increase up to traffic profile 6. From traffic profile 6 on, the gain becomes quite stable, hovering around $\sim 60\%$. Concerning the impact of k , the higher the k is, the higher the gain is realized at specific traffic scenarios. It can be explained by the fact that the more paths are introduced in network, the more chances of adaptation that FlexRate offers.

Next, we perform a study to investigate the maximum supported traffic with FlexRate by incrementally increase the

TABLE I: Reach-Rate model

Rate [Gbps]	Maximum Reach [km]
$r = 100$	$d_{max} = 2000$
$r = \{90, 80, 70, 60\}$	d_{max} satisfies : $r = 100 - 40\%.100. \frac{d_{max}-2000}{1000}$
$r = \{50, 40\}$	d_{max} satisfies : $r = 60 - 40\%.60. \frac{d_{max}-3000}{1000}$
$r = \{30, 20\}$	d_{max} satisfies : $r = 36 - 40\%.36. \frac{d_{max}-4000}{1000}$
$r = 10$	d_{max} is assumed to be longer than any path

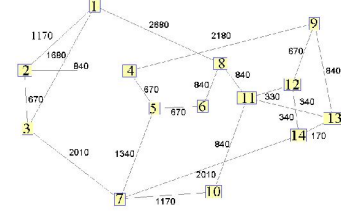


Fig. 2: 14-nodes NSF network topology

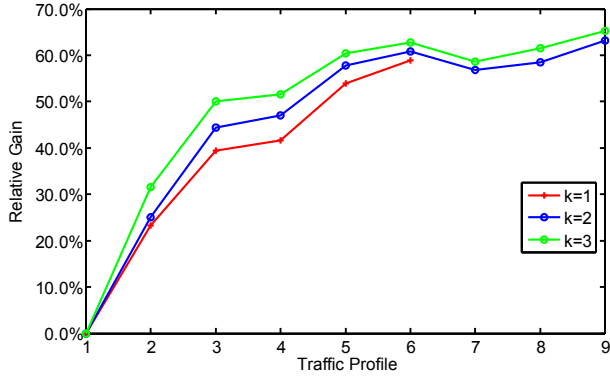


Fig. 4: Maximum link load reduction in percentage

traffic with a step of 10 Gbps until it can not be supported. Figure 5 shows the result of maximum traffic profile being supported by FlexRate and MLR corresponding to different values of k . Thanks to finer rate adaptation, FlexRate could support traffic around three times higher than MLR.

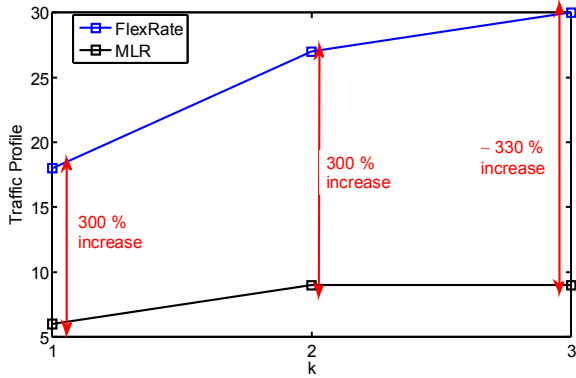


Fig. 5: Maximum supported traffic comparison

V. CONCLUSION

In this paper, we discussed the flexible rate optical networking based on FEC variation where a trade-off between capacity and transmission distance is observed. We formulated a transparent network planning taking into account the variation of rate over transmission reach. A case study was presented and shown that FlexRate enabled by variable-rate FEC exhibits

significant spectrum efficiency over MLR thanks to its finer rate adaptation over optical reach. That increase of spectrum efficiency leads to significant reduction of maximum link load up to $\sim 60\%$ compared with MLR, and in turn, allow FlexRate supporting total traffic around three times higher than MLR.

This paper is our early-stage work on network impact of flexible rate transmission introduced by recent advances in adaptive FEC schemes. For future works, problems could be addressed such as considering protection requirement, or impact of combining modulation format and FEC adaptation. Dynamic version of network provision is also worth of further studies.

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