Explore Maximal Potential Capacity of WDM Optical Networks Using Time Domain Hybrid Modulation Technique

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Abstract—The recent emerging time domain hybrid modulation (TDHM) technique is considered promising because it can realize continuous adaptation between spectral efficiency and transparent reach through appropriately allocating the time slot occupancy ratios of different modulation formats in a time-division multiplexing (TDM) frame. This technique is expected to achieve more efficient spectrum utilization or higher transmission capacity than the traditional transmission technique based on discrete modulation formats. For the point-to-point transmission system, the benefit of the TDHM technique has been experimentally verified. However, its benefit from the whole network perspective has not been explored yet. In this paper, we apply the TDHM technique to the optical network to maximize its transmission capacity. To evaluate the benefit of this technique, we consider the routing and wavelength assignment (RWA) problem for the TDHM-based WDM network, for which we develop an Integer Linear Programming (ILP) model and a waveplane-based heuristic algorithm to maximize the total network transmission capacity for the cases with and without network protection. For the protection case, the shared backup path protection (SBPP) technique is employed owing to its efficiency of spare capacity sharing and simplicity in network operation. The simulation study shows that compared to the design with discrete modulation formats, the TDHM-based approach can significantly increase the network transmission capacity.

Index Terms—Time domain hybrid modulation (TDHM), rate adaptive optical network, waveplane-based heuristic algorithm, network capacity

I. INTRODUCTION

Due to the fast growth of the Internet traffic, next generation optical networks are expected to be more flexible and spectrally efficient. To increase the data rate and spectral efficiency of an optical network, high-order modulation formats such as Quadrature Amplitude Modulation (QAM) have been employed, which however requires a higher optical signal to noise ratio (OSNR) tolerance, and therefore inevitably limits the transparent reach of a lightpath [1]. Much effort has been made to design flexible transceivers that can provide flexible bandwidth and achieve the best spectral efficiency based on the current network traffic demands and fiber-link conditions [2-4]. The state-of-the-art optical transceiver can dynamically change its bit rate, modulation format, FEC type, etc. for each optical channel to tailor the transmission OSNR requirement. However, such an adaptation is still based on a discrete manner to choose a discrete 2^m-QAM modulation format, which makes the adaptation between spectral efficiency and transparent reach also discrete [5][6]. As such, in the traditional rate and modulation format adaptive system [7], when the physical distance of an optical channel is between the transparent reaches of two modulation formats (e.g., BPSK and QPSK), a lower level modulation format (e.g., BPSK) will have to be used for its higher OSNR tolerance. This would cause the wastage of spectrum resource for the optical channel.

The recent emerging TDHM technique is promising to remedy the above disadvantage suffered by the discrete modulation scheme [5][6][8-16]. By properly designing a TDM frame and allocating the time slot occupancy ratios of different modulation formats in the frame, the TDHM technique can achieve a continuous adaptation between spectral efficiency and transparent reach of an optical channel, which can assign the most spectrally efficient TDHM frame to match the physical layer transmission condition of an optical channel and therefore achieve the most efficient spectrum utilization. The TDHM technique is compatible to the standard ITU-T frequency spacing, which as an important advantage does not require upgrading or changing today’s optical switch nodes such as reconfigurable optical add/drop multiplexer (ROADM) [8][9].

The TDHM technique has been experimentally verified in a point-to-point optical transmission system. However, whether the technique is still spectrally efficient under the circumstance of an entire network is still an open question. In this paper, for the first time we apply this technique to an optical transport network. We aim to evaluate the benefit of this technique in increasing the whole network transmission capacity. We specifically consider the RWA problem for a TDHM-based WDM network. To fully explore the potential of the TDHM technique in increasing the network transmission capacity, we develop Integer Linear Programming (ILP) models and efficient waveplane-based heuristic algorithms.
Moreover, two scenarios, i.e., without and with network protection, are considered, respectively. In particular, for the protection scenario, the SBPP technique is employed for performance evaluation owing to its high spare capacity sharing efficiency and simplicity in network operation [17][18]. Simulation results show that the TDHM technique is effective to significantly increase the total network transmission capacity compared to the design based on the discrete modulation scheme either for the case without protection or with SBPP protection.

The rest of the paper is organized as follows. In Section II, we introduce the basic concept of the TDHM technique and illustrate its benefit in increasing the optical channel capacity. For the RWA problem of the TDHM-based WDM network, we develop ILP models and efficient waveplane-based heuristic algorithms in Sections III and IV, and two scenarios, i.e., with and without network protection, are considered. In Section V, study cases and test conditions are described, and the results of different approaches are presented and discussed. Section VI concludes the paper.

A. Literature Review

Much effort has been made to develop the TDHM technique with different combinations of modulation formats. Peng et al. [10] initially demonstrated the 4QAM&8QAM hybrid technique to transmit a 112-Gb/s single carrier ultra-dense WDM channel over a fixed 25-GHz spectrum grid. Zhou et al. [11-13] demonstrated the TDHM technique using different modulation format combinations in several experiments and proved the possibility of placing 400-Gb/s signals on the conventional 50-GHz or 100-GHz channel grid. Zhuge et al. [6][14][15] successfully demonstrated the TDHM transmission in the environments of both fixed grids and future flex-grids by employing high-speed digital to analogue converters (DACs) at transmitters and low-complexity digital signal processors (DSPs) at receivers. Curri et al. [16] investigated the transmitter operation strategies for the TDHM technique and showed pre-distortion and polarization interleaving can help alleviate the penalty induced by nonlinear propagation.

On the other hand, the mixed line rate (MLR) WDM network is another type of popular network architecture that adopts adaptive discrete rates. Its design problem, i.e., routing/wavelength/rate assignment (RWRA), can be extended from the traditional RWA problem [19][20]. In [7], Nag et al. proposed a design method for the MLR optical network with transceivers that employ different modulation formats. An ILP model was formulated to determine a minimum-cost solution for such a type of network by imposing a signal-quality constraint on the feasibility of lightpaths. In [21], Christodouloupolous et al. developed RWA algorithms that can adapt the transmission reach of each connection according to the use of the modulation formats/line rates in the MLR network. Batayneh et al. [22] considered the cost-efficient routing problem for carrier Ethernet connections in an MLR network with transmission reach constraints. Both an ILP and a heuristic algorithm were developed and evaluated.

Meanwhile, some works have focused on survivability of the MLR network. Liu et al. [23] addressed the problem of providing dedicated protection for the MLR optical network. They also extended their former work to design an MLR network with shared sub-connection protection (SSP) [24]. In addition, Vadrevu et al. [25] proposed a computationally efficient method for provisioning degraded services (or partial-protection) in a MLR network with multi-path routing.

For network protection, shared backup path protection (SBPP) is considered as one of the most promising techniques due to its advantages of operational simplicity, high restoration speed, and high spare capacity efficiency [18]. SBPP is a failure-independent preplanned path-oriented technique where the working and protection routes of each protected service must be link disjoint and protection capacity is cross-connected on the protection route in real time. High protection capacity efficiency can be realized by protection capacity sharing on the common links of different protection lightpaths whose corresponding working lightpaths do not share any common link. 1+1 path protection (also called dedicated path protection) [17] is also considered in the study for performance comparison. The 1+1 path protection technique is the same as the SBPP technique in establishing working and protection lightpaths, except that the 1+1 technique does not allow protection capacity sharing among protection lightpaths.

II. TIME DOMAIN HYBRID MODULATION TECHNIQUE

The TDHM technique transmits multiple modulation formats interleaved in the time domain, which has been experimentally verified to be generated and reconfigured by employing DAC-enabled transmitters for spectrum shaping, pre-equalization, and flexible modulation formats [5][6]. At the receiver, modulation format-transparent DSPs are employed to process a TDHM signal and the computational complexity of the DSPs can be as low as a standard single format transceiver [6]. Fig. 1 shows a specific TDM transmission frame mixed by the QPSK and 16QAM formats with the configuration of 1:1 occupancy ratio. This TDHM frame can be represented as QPSK&16QAM ($p_1$, $p_2$), where $p_1$ and $p_2$ are the probabilities of the two modulation formats in the frame, and $p_1 + p_2 = 1$. Under this configuration, there is 50% transmission of the QPSK and 16QAM symbols in the time domain, respectively.

![Fig. 1. QPSK&16QAM (0.5, 0.5) frames with SE=3 bit/symbol.](image-url)

The spectral efficiency (SE) of a TDHM symbol, i.e., bits per symbol, can be calculated as:

$$SE = \sum_{i \in Q} p_i \cdot SE_i \text{ bit/symbol}$$  \hspace{1cm} (1)
where $p_i$ is the occupancy ratio of a particular modulation format in a frame and $SE_i$ is the spectral efficiency of this modulation format. $Q$ is the set of modulation formats used in the frame. In Fig. 1, $SE_1$=2 bit/symbol for QPSK and $SE_2$=4 bit/symbol for 16QAM. Thus, the SE of a QPSK&16QAM ($p_1$, $p_2$) signal can range from 2 to 4 bit/symbol, and the line rate (LR) of an optical channel modulated by this signal is

$$LR = SE \times 2R \text{ bit/s}$$  (2)

where $R$ is the baud rate of the signal in units of symbol/s, and because the optical transmission system is assumed to employ polarization division multiplexing (PDM), number “2” corresponds to the x-polarization and the y-polarization of PDM. Assuming the baud rate of an optical channel is fixed, the line rate of the channel is only determined by $SE$, which is further dependent on the $\{p_i\}$ distribution of modulation formats in a frame.

The choice of $p_i$ will affect the transparent reach of an optical channel, which has been explained in [6]. The effect of physical-layer impairments may become stronger when bit rate (or spectral efficiency) of an optical channel becomes higher. Hence for a given bit error rate (BER) requirement, a higher bit rate or a higher SE signal requires a higher OSNR, and therefore inevitably limits the transparent reach of a lightpath. Based on (1), we can see that $p_i$ determines the spectral efficiency of a TDHM signal, which will further affect its transparent reach. In addition, in order to maintain the same BER level, a high order modulation format in each TDHM frame should increase its power level since it is more sensitive to noise [6].

To increase the line rate of an optical channel, a maximal achievable $SE$ of the channel should be used. The experimental curve in Fig. 2 [6] interpolates the relationship between the maximal achievable spectral efficiency (i.e., bit/symbol) and the transparent reach of an optical channel under a fixed 28G symbol/s baud rate and 50-GHz frequency spacing, for which an attenuation coefficient 0.8 is set to offset the influence of the ideal laboratory environment. In the figure, we see that the maximum reaches of a pure QPSK and 16QAM are 5,118 km and 850 km, respectively.

![Fig. 2. Transparent reach versus spectrum efficiency.][1]

We use an example as shown in Fig. 3 to explain the benefit of the TDHM technique when establishing multiple SBPP-survivable channels in an optical network. Assume there are two SBPP service connections (i.e., S1 and S2), whose working lightpaths are L1 (1-2-5) and L2 (1-3), respectively, and corresponding protection lightpaths are P1 (1-4-5) and P2 (1-4-3), respectively.

![Fig. 3. Example of lightpath establishment in a TDHM-based SBPP network.][2]

For S1, if the traditional discrete modulation scheme is applied, then both of the working and protection lightpaths should use QPSK, which corresponds to a 2-bit/symbol $SE$. In contrast, if the TDHM technique is employed, then more efficient spectrum utilization can be achieved with L1 having a 3.291-bit/symbol $SE$ and P1 having a 2.741-bit/symbol $SE$. To ensure 100% network protection, we would take the same spectral efficiency for the working and protection lightpaths, i.e., 2.741 bit/symbol, which corresponds to a 37.05% increase of protected transmission capacity for S1 compared to the discrete modulation scheme. For S2, we can make a similar analysis. Table I shows the detail on the related SE data under the different modulation schemes.

**Table I. Comparison of Spectral Efficiency of Protected Lightpath Services Based on Different Modulation Schemes**

<table>
<thead>
<tr>
<th>SBPP service</th>
<th>Lightpath</th>
<th>Spectral efficiency (bit/symbol)</th>
<th>% of increased capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>L1</td>
<td>3.291</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>P1</td>
<td>2.741</td>
<td>2</td>
</tr>
<tr>
<td>S2</td>
<td>L2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>P2</td>
<td>3.059</td>
<td>2</td>
</tr>
</tbody>
</table>

In addition, in the context of the example in Fig. 3, the SBPP technique allows the two protection lightpaths to share a common wavelength on link (1-4) as the two corresponding working lightpaths do not share any common link. In contrast, under the 1+1 path protection technique, no protection capacity sharing is allowed on link (1-4). Thus, two dedicated protection wavelengths are required on the link.

**A. Application of TDHM Technique**

The traditional WDM network may transmit the same line rate or mixed line rates on different optical channels. From the uniform line rate to the mixed line rates, it has been a big capacity upgradeation for the WDM network to squeeze its maximal capacity potential. However, even employing the mixed line rates, due to the non-continuousness of the line rates of different modulation formats, we still find that the maximal transmission capacity of an optical channel cannot be fully explored, just as illustrated by the network example in Fig. 3. This is because between two neighboring discrete modulation formats, there is a big non-continuous spectrum efficiency gap. The TDHM technique can make the relationship between the spectrum efficiency of an optical channel and its transparent reach continuous as shown by the curve in Fig. 2. This enables to maximally transmit the potential capacity of each optical channel according to its actual physical-layer transmission condition (e.g., distance).
thereby greatly increasing its transmission capacity.

As an application scenario of the TDHM technique, we can start from a traditional WDM network. To support the TDHM technique, we first replace standard WDM transponders with TDHM-enabled WDM transponders. Then according to the transmission distance of each optical channel, we choose a certain distribution of occupation ratios of different modulation formats to enable the transparent reach of a THDM signal to be just enough to cover the distance of the optical channel. In this application, we do not need to replace any optical switch node (e.g., ROADM) or change the spectrum operational mode (e.g., from fixed grid to flexi-grid). However, we can significantly increase the whole network transmission capacity with the same spectrum resources. This application is especially suitable for the case of static lightpath routing and optical channel establishment, under which all the channel routes are known and thus we can assign the most efficient TDHM signals to maximize their channel transmission speeds. Of course, it may also be possible to support the dynamic lightpath routing scenario if the techniques of software-defined optical networks [26] and real-time optical signal monitoring and estimation [27] become mature. For a real-time optical channel route, we can assign the most efficient TDHM signal to the optical channel to maximize its transmission capacity.

In summary, the application of the TDHM technique is based on the following standing point: since there have been optical channels established in the traditional WDM network, why not we explore the highest potential capacity over these channels, which does not need to consume any extra wavelength resource, though required to replace with the TDHM-enabled transponders.

As another application scenario, we can also apply the TDHM technique to a flexi-grid optical network. Some previous works have experimentally verified the feasibility of generating and transmitting the TDHM signal in this type of network [6][14]. From the perspective of network planning and design, the TDHM technique can be applied to further maximize the total transmission capacity of the flexi-grid optical network given limited spectrum resource. Different from the scenario of a WDM network, the TDHM technique can affect the number of frequency slots (or number of subcarriers) assigned to each optical channel for a certain bit rate. We can extend the present work to solve the TDHM-based routing and spectrum assignment (RSA) problem for the flexi-grid optical network.

III. OPTIMIZATION DESIGN FOR TDHM-BASED WDM OPTICAL NETWORK

To evaluate the potential benefit of the TDHM technique in the context of a whole network, we consider the RWA problem of a TDHM-based WDM network to maximize its total transmission capacity. We firstly define the research problem and then formulate the problem with a path-arc ILP optimization model.

A. Problem Statement

Given a network topology \(G(V, E)\), where \(V\) is the set of nodes and \(E\) is the set of (bi-directional) fiber links. Assume the number of demand units between each node pair in the network is also known a priori, which forms a lightpath traffic demand matrix. In addition, between each node pair, multiple routes are pre-determined and used for lightpath establishment.

The constraints of the RWA problem include: (1) The physical-layer capacity constraint, i.e., a limited number of wavelengths in each fiber link; (2) The wavelength continuity constraint that requires all the links traversed by a lightpath must use the same wavelength; (3) The OSNR tolerance constraint for each optical channel, under which a limited maximal SE can be reached for a certain transparent reach; (4) When considering SBPP network protection, 100% failure protection should be guaranteed for each service connection and moreover maximal spare capacity sharing should be achieved among protection lightpaths when their corresponding working lightpaths do not share any common link. Note that in this study we assume that the optical transponders at each node are fully tunable such that the working and protection lightpaths of each SBPP service may use different wavelengths.

The objective of the optimization problem is to maximize the total transmission capacity in the TDHM-based optical network and meanwhile to minimize the network spare capacity redundancy when SBPP protection is considered.

Based on the given input parameters and subject to the aforementioned constraints, we next present the ILP models for the RWA problem of the TDHM-based optical network. We first present the model for the case without network protection, which is followed by the model for the TDHM-based SBPP optical network.

B. ILP Model without Network Protection

Sets:

- \(L\): The set of network links.
- \(D\): The set of node pairs.
- \(W\): The set of wavelengths in each fiber link.
- \(R^d\): The set of candidate routes between node pair \(d\), which are used for lightpath establishment.

Parameters:

- \(\rho^d_{i,r}\): A binary parameter that takes the value of 1 if link \(i\) is traversed by path \(r\) between node pair \(d\); 0, otherwise.
- \(C_d\): The number of lightpath demand units between node pair \(d\). Each demand unit corresponds to an optical channel.
- \(S^d_{\alpha,r}\): The maximal allowed line rate for an optical channel on path \(r\) between node pair \(d\). This line rate can be obtained according to the \(SE\) of the optical channel by controlling the \(\{p\_\alpha\}\) distribution of the modulation formats in a TDHM frame.

Variables:
The number of lightpath demand units served by candidate path \( r \) between node pair \( d \).

A binary variable that takes the value of 1 if wavelength \( \omega \) on candidate path \( r \) between node pair \( d \) is used to establish a lightpath channel; 0, otherwise.

Objective:
Maximize \( \sum_{d \in D, r \in R} T^{d,r} \cdot S^{d,r} \) \hspace{1cm} (3)
Subject to:
\( \sum_{r \in R} T^{d,r} \leq C_d \) \hspace{1cm} \( d \in D \) \hspace{1cm} (4)
\( T^{d,r} = \sum_{\omega \in W} \phi^{d,r}_{\omega} \) \hspace{1cm} \( \forall d \in D, \forall r \in R^d \) \hspace{1cm} (5)
\( \sum_{d \in D, r \in R} \rho^{d,r}_{\omega} \cdot \phi^{d,r}_{\omega} \leq 1 \) \hspace{1cm} \( \forall \omega \in W, \forall i \in L \) \hspace{1cm} (6)

Objective (3) is to maximize the total transmission capacity of the lightpaths established in the network. The total network transmission capacity is not only determined by the number of established lightpaths, but also by the line rates of the optical channels. Constraint (4) ensures that the number of established lightpaths must be no greater than the number required by each node pair. Constraint (5) sums the total established optical channels on all the wavelengths of the paths between node pair \( d \). Constraint (6) ensures that any wavelength on a link can only be assigned to a single lightpath channel.

The computational complexity of the ILP model is decided by the dominant numbers of variables and constraints. In the above model, the dominant number of variables is \( O(|D| \cdot |R^d| \cdot |W|) \), and the dominant number of constraints is \( \max\{O(|D| \cdot |R^d|), O(|W| \cdot |L|)\} \), where \( |D| \) and \( |L| \) are the total numbers of node pairs and links in the network, respectively, \( |W| \) is the number of wavelengths in each fiber link, and \( |R^d| \) is the number of candidate routes between each node pair.

C. ILP Models with Network Protection

In this part, we present an ILP model to maximize the protected capacity and to minimize the spare capacity redundancy for a TDHM-based SBPP optical network. We assume that between each node pair, there is only a single shortest path for working lightpath establishment and multiple candidate paths that are link-disjoint from the working path for protection lightpath establishment.

The sets for the SBPP-based ILP model are the same as those of the unprotected model, except that \( R^d \) should be the set of candidate protection routes between node pair \( d \) with the primary route between each node pair pre-determined. In addition, parameter \( C_d \) is kept for the SBPP model to represent the number of protected lightpath channels between each node pair. We have additional parameters and variables for the SBPP model as follows.

Parameters:
\( \sigma^{j}_{d} \) A binary parameter that equals 1 if the failure of span \( j \) hits the working path of node pair \( d \); 0, otherwise.
\( \rho^{d,r}_{\omega} \) A binary parameter that equals 1 if the \( r^{th} \) candidate protection path between node pair \( d \) crosses span \( i \).

A binary parameter that equals 1 when the working path of node pair \( d1 \) and protection path \( r \) between node pair \( d1 \) share a common link; 0, otherwise.

A binary parameter that equals 1 when the working paths of node pairs \( d1 \) and \( d2 \) share common link(s); 0, otherwise.

The maximal allowed line rates for an optical channel on the working path.

The maximal allowed line rates for the \( r^{th} \) protection path between node pair \( d \).

A weight factor.

Variables:
\( W^d \) The number of working lightpath channels established between node pair \( d \).
\( B^{d,r} \) The number of protection lightpath channels established on protection path \( r \) between node pair \( d \).
\( f^d \) The achievable protected transmission capacity between node pair \( d \), which requires the corresponding working and protection lightpaths to transmit the same capacity for 100% protection.
\( s_i \) The number of protection wavelengths reserved on link \( i \).
\( \phi^{d,r}_{\omega} \) A binary variable that takes the value of 1 when wavelength \( w \) is used by the working lightpath of node pair \( d \) subject to the constraint of wavelength continuity; 0, otherwise.
\( \phi^{d,r}_{k} \) A binary variable that takes the value of 1 when the protection lightpath between node pair \( d \) is established on the \( r^{th} \) protection route and it uses wavelength \( k \); 0, otherwise.

The objective and the constraints of the SBPP model are as follows.

Objective:
Maximize \( \sum_{d \in D} f^d - \alpha \sum_{i \in L} s_i \) \hspace{1cm} (7)
Subject to:
\( f^d \leq s^d_w \cdot W^d \) \hspace{1cm} \( \forall d \in D \) \hspace{1cm} (8)
\( f^d \leq \sum_{r \in R^d} s^{d,r}_w \cdot B^{d,r} \) \hspace{1cm} \( \forall d \in D \) \hspace{1cm} (9)
\( s_i \geq \sum_{d \in D, r \in R^d} \sum_{k \in W} \phi^{d,r}_{k} \cdot \rho^{d,r}_{\omega} \cdot \sigma^{j}_{d} \) \hspace{1cm} \( \forall i, j \in L, i \neq j \) \hspace{1cm} (10)
\( W^d = \sum_{r \in R^d} B^{d,r} \) \hspace{1cm} \( \forall d \in D \) \hspace{1cm} (11)
\( W^d \leq C_d \) \hspace{1cm} \( \forall d \in D \) \hspace{1cm} (12)
\( W^d = \sum_{w \in W} \phi^d_w \) \hspace{1cm} \( \forall d \in D \) \hspace{1cm} (13)
\( B^{d,r} = \sum_{k \in W} \phi^{d,r}_{k} \) \hspace{1cm} \( \forall d \in D, r \in R^d \) \hspace{1cm} (14)
\( \sum_{d \in D} \theta^{d,r}_{\omega} \cdot \phi^{d,r}_{w} \leq 1 \) \hspace{1cm} \( \forall w \in W, j \in L \) \hspace{1cm} (15)
\( \theta^{d,r}_{\omega} + \phi^{d,r}_{k} + \rho^{d,r}_{\omega} \cdot \theta^{d,r}_{\omega} \leq 2 - \theta^{d,r}_{\omega} \) \hspace{1cm} \( \forall i \in L, k \in W, d1, d2 \in D, r \in R^{d1}, p \in R^{d2}, d1 \neq d2 \) \hspace{1cm} (16)
\( \delta^{d,r}_{d1} \cdot (\theta^{d,r}_{w} + \phi^{d,r}_{w}) \leq 1 \) \hspace{1cm} \( \forall w \in W, d1, d2 \in D, r \in R^{d2}, d1 \neq d2 \) \hspace{1cm} (17)
In objective (7), the first term is to maximize the total network-wide protected capacity and the second term is to minimize the total reserved protection wavelength capacity in all the fiber links. In this way, we can get a solution with the maximum total network-wide protected capacity and meanwhile ensure a relatively low reserved protection wavelength capacity. Here $\alpha$ is a weight factor, which is a small value such that the first objective has a higher priority. In this study, we set $\alpha=0.01$.

Constraints (8) and (9) jointly find the maximal achievable protected transmission capacity between each node pair, in which for a specific node pair $d$, $f^d = min\{s^d_w, s^d_b\}$ and it is the net protected capacity of an optical channel with 100% failure protection. Constraint (10) ensures that there is sufficient protection wavelength capacity reserved in each link used for establishing the protection lightpaths. Constraint (11) ensures that for each node pair the number of established protection lightpath channels must be equal to the number of established working lightpath channels. Constraint (12) ensures that the number of established working lightpath channels does not exceed that of SBPP demand units required by users. Due to (11), this constraint inherently ensures that the number of established protection lightpath channels does not exceed that of the required SBPP demand units. Constraints (13) and (14) sum the total established working and protection lightpath channels on all the wavelengths between node pair $d$, respectively. Constraint (15) ensures that there is maximally one working lightpath channel occupying a wavelength in any fiber link. Constraint (16) ensures the condition of spare capacity sharing among protection lightpath channels. Constraint (17) ensures that each wavelength in any fiber link can only be used by either a working lightpath channel or a protection lightpath channel.

In the above ILP model, the working route between each node pair is fixed; however, the protection route for each protection lightpath channel can be different, chosen from a predetermined route set $R^d$. Thus, this is type of lightpath channel-based SBPP; that is, the SBPP protection is implemented on the basis of each lightpath channel. In addition, the computational complexity of the model is as follows: the dominant number of variables is $O(|D| \cdot |R^d| \cdot |W|)$ (due to variable $q^d_k$) and the dominant number of constraints is $O(|L| \cdot |D|^2 \cdot |R^d| \cdot |W|)$ (due to constraint (16)).

Based on the SBPP ILP model, we can easily extend to obtain a similar model for the 1+1 path protection technique by disallowing protection lightpaths to share protection capacity. The key differences are as follows. The parameter $\theta_{\alpha\gamma}_{11}$ is not required. Constraint (10) changes to be $s_1 \geq \sum_{d\in D, r\in R^d, k\in W} p_{dr}^d \cdot q_{k}^d$ and (16) changes to be $p_{d1,r}^d \cdot q_{k}^d + p_{d2,p}^d \cdot q_{k}^d \leq 1$ because 1+1 path protection does not allow protection capacity sharing among backup paths.

IV. HEURISTIC APPROACHES FOR SUB-OPTIMAL DESIGN

The ILP models will find optimal solutions to the TDHM-based RWA problems, which however is NP-complete. To reduce the computational complexity, it is desirable to develop an efficient heuristic algorithm for the TDHM-based RWA problems. In this study, we extend the traditional waveplane-based RWA algorithm [28] for the TDHM-based RWA problems. In addition, we introduce a multi-iteration process to consider multiple shuffled demand sequences and choose the demand sequence with the best performance in order to alleviate the performance influence because of different demand orders [29]. The related concepts are as follows.

A. Heuristic Algorithm

We first describe the algorithm for protected lightpath service establishment in a TDHM-based WDM network. The algorithm for the case without protection can be easily extended by removing the step for protection lightpath establishment.

For the TDHM-based network, to establish an SBPP service, we scan the waveplane list for both working and protection lightpaths. To search an optimal protection route on a waveplane, we apply a least cost (LC) strategy for maximal protection capacity sharing among protection lightpaths. Specifically, for protection path searching we set the cost of wavelength link that is free or sharable on each waveplane as $d_i/(k_i + 1)$ (18) where $d_i$ is the physical length of link $i$ and $k_i$ is the number of protection lightpaths that share the wavelength link. This means that the link cost will be lower if there are more protection lightpaths sharing it and the link is just equal to its physical distance when the wavelength link is free. The cost setting is reasonable for maximally sharing protection capacity.
and reserving more free capacity for the future connections. Based on the concept of waveplane, we present the heuristic algorithm for solving the SBPP RWA problem as follows.

Algorithm 1: Waveplane-based heuristic algorithm for the SBPP RWA problem

**Input:** A network topology $G(V,E)$ and a shuffled demand sequence $S$.  
**Output:** Maximal protected network capacity and required protection capacity.

1. Generate $W$ parallel waveplanes based on the number of wavelengths in each fiber link.
2. Employ $k$-disjoint shortest path searching algorithm to find the shortest route $R$ as the working path and all the other eligible paths that are link disjoint from $R$ as backup path set $R^d$ for node pair $d$.  
3. For each lightpath demand $d$ in $S$ do
   4. For each waveplane $w$ do
      5. Try to establish a working lightpath on the waveplane;
         If successful then
            6. Break the previous for-loop;
         Else
            7. Move to the next waveplane;
         End if
      8. End for
   9. If failed to establish a working lightpath on all waveplanes then
      10. Block demand $d$ and move to next demand;
   Else
      11. For each waveplane $w$ do
         12. For each candidate protection route in $R^d$ of demand $d$ do
            13. Try to establish a protection lightpath on the waveplane;
               If successful then
                  14. Record the route and waveplane index;
               Else
                  15. Try the next candidate protection route in $R^d$;
               End if
         16. End for
      17. Find a protection route with the least cost from all the routes recorded in the previous for-loop;
      18. If an eligible protection route $P$ is found then
         19. Establish the protection lightpath on the waveplane and find the maximal line rate for this route. Update the costs of wavelength links traversed by the established protection lightpath;
         20. Else
            21. Block demand $d$;
         End if
      22. End if
   End for
30. Synchronize the waveplane state and move to next demand in sequence $S$;
32. Sum the total protected capacity of all the SBPP lightpath services in the network.

In the algorithm, the working route between each node pair is fixed; however, the protection route for each protection lightpath channel can be different, chosen from a predetermined route set $R^d$. This setting is to match the setting of the previous ILP model. The waveplane-based heuristic algorithm is efficient to consider all possible waveplanes for the working and protection lightpaths. It is also efficient to enable maximal spare capacity sharing among the protection lightpaths with (18).

According to the proposed heuristic approach, we can see that only when both the working and protection lightpaths are established successfully, can an SBPP connection be established. When choosing a protection route on a waveplane, the spare capacity sharing condition must be checked; only a protection wavelength link whose protected working lightpaths do not share any common link(s) with the current working lightpath can be shared for establishing the current protection lightpath.

We extended the waveplane-based algorithm in the literature [28] in this study for purposes of performance evaluation. The algorithm has been verified to be efficient compared to the other approaches in our previous studies [28][30]. The extended heuristic algorithm helps maximize the network capacity from the following two perspectives. First, through waveplane-based routing and wavelength assignment, we can maximize the total number of routed optical channels given limited network resource in each fiber link. Second, for each established optical channel, the TDHM technique is employed to maximize its bit rate based on its physical layer transmission condition. Both the efforts aim to maximize the total network transmission capacity. However, maximizing the number of established channels should have a higher priority since the TDHM technique increases the capacity only for an existing channel. Without channels established, no matter how advanced the TDHM technique is, no capacity can be provisioned.

The computational complexity of the heuristic algorithm is analyzed as follows. To establish an SBPP service for each node pair, the heuristic algorithm consists of three key steps. In the first step, it searches for the working route and the corresponding protection router set for each node pair, which corresponds to computational complexity of $O(|N|^2 + |R^d| \cdot |N|^2)$, where $|N|$ is the total number of nodes in the network, $|R^d|$ is the number of protection routes per node pair, the first $|N|^2$ is for working route searching, and $|R^d| \cdot |N|^2$ is for protection route set searching. In the second step, it tries to establish a working lightpath, which in the worst case may have to check all the waveplanes. Thus, it is computational complexity is $O(|W| \cdot |L|)$, where $|W|$ is the number wavelengths in each fiber link and $|L|$ is the total number of links in the network. In the third step, it checks all the eligible backup routes in the set of $R^d$ on all the waveplanes to find a backup path with the least cost, of which the computational complexity is $O(|R^d| \cdot |W| \cdot |L|)$. Thus, to
establish an SBPP service for each node pair, the overall computational complexity of the waveplane-based algorithm is \( O \left( |R|^2 \cdot (|N|^2 + |W| \cdot |L|) \right) \).

The above algorithm can be easily extended for 1+1 path protected lightpath service establishment by disallowing spare capacity sharing among protection lightpaths.

For the case without network protection, we can also simply extend the above SBPP algorithm without establishing protection lightpaths. To enhance the performance, rather than a single shortest route as in the algorithm for SBPP, we try multiple routes for working lightpath establishment. Specifically, to choose the shortest route for maximizing the TDHM benefit, we have incorporated a step in the algorithm that scans all the waveplanes to choose a route that has the smallest number of hops, and if there are multiple routes with the smallest number of hops, we choose the one with the shortest physical distance. We consider the smallest number of hops as the first objective because we wish to minimize the consumed wavelength resources so that more optical channels can be provisioned, after which we further consider to choose the shortest route (in distance) among the routes with the same number of hops for the maximal TDHM potential. The computational complexity of this waveplane-based heuristic algorithm is \( O(|W| \cdot |N|^2) \).

V. TEST CONDITIONS AND RESULTS

A. Test Conditions

We evaluated the performance of a TDHM-based optical network by running simulations for three test network, including (1) a six-node, nine-link (n6s9) network, (2) the 10-node, 22-link (SmallNet) network, and (3) the 24-node, 43-link US backbone network (USNET) as shown in Fig. 5. The number close to each link is its physical distance in units of km. Note that, as case studies, the link distances are not actual ones, but are scaled with a certain ratio. To consider the situations of different numbers of wavelengths in each fiber link, we assume that there are a maximum of 16 wavelengths in each fiber link in the n6s9 network and the SmallNet network, and 80 wavelengths in the USNET network. In addition, the number of lightpath demand units between each node pair is assumed to uniformly range from 1 to 5 units (i.e., optical channels) in all the networks. Note that for the traffic demand, we assume to be based on the number of optical channels between node pairs. This assumption is based on the application scenario of the TDHM technique to upgrade the capacity of an existing WDM network, in which optical channels are assumed to have existed between node pairs. These channels however do not carry the maximal transmission capacity under the discrete modulation approach. If the TDHM technique is applied, we aim to see how much extra capacity can be freely upgraded for the existing channels. We think that a study based on such a traffic demand assumption can best reflect or highlight the benefit of the TDHM technique. The QPSK&16QAM \( (p_1, p_2) \) symbol is employed for data transmission on each optical channel, which has a fixed baud rate of 28-G symbol/s and is established on a 50-GHz frequency grid.

For the ILP model, in the case of a network without protection, we employ the \( k \) disjoint shortest path algorithm to find all the routes between each node pair for the study. All the routes have distances shorter than 5,118 km. In this study, we are considering regeneration-free optical network design; if there are node pairs whose shortest routes are longer than 5,118 km, then no modulation format is suitable for transparent lightpath establishment, while requiring signal regenerators in the middle of the lightpaths. For the TDHM-based SBPP ILP model, between each node pair, we assign the shortest route to the working lightpath and all the other routes that are link-disjoint from the working route to form a candidate protection route set.

We employed the commercial AMPL/Gurobi [31] software package (version 5.0.0) to solve the two ILP models on a 64-bit server with 2.4-GHz CPU and 8-G memory. The MIPGAP of the ILP models are set to be 0.01%. For the heuristic algorithm, we shuffle an initial lightpath demand list 1000 times to form the shuffled demand sequences, for each of which we run the heuristic algorithm and select the demand sequence with the best design performance (i.e., the maximal transmission capacity and minimum spare capacity redundancy) as the final solution.

To verify the performance of the proposed approaches, we also compare the performance of the scheme based on the pure discrete line rate adaptation, in which the discrete modulation formats of pure QPSK and 16QAM are considered. The proposed approaches were also compared to the schemes based on fixed shortest path routing and first-fit wavelength assignment. In addition, the performance of the SBPP scheme is compared with that of 1+1 path protection both under the TDHM technique.

![Network Diagrams](image_url)

(a) 6-node, 9-link n6s9 network (b) 10-node, 22-link SmallNet network (c) 24-node, 43-link US backbone network (USNET)

Fig. 5. Test networks (unit of link length: km).
B. Total Network Transmission Capacity

We evaluate how the TDHM technique can help increase network transmission capacity through considering two cases, without and with network protection. Fig. 6 shows the results of the case without protection, in which the x-axis is the number of traffic demand units between each node pair and the y-axis is the total network transmission capacity in Gb/s. Three design approaches are compared, including (1) “Shortestpath-TDHM” and “Shortestpath-Discrete,” which corresponds to the approaches of using the fixed shortest path routing algorithm and the first-fit wavelength assignment strategy with the TDHM and discrete modulation schemes, respectively; (2) “Waveplane-TDHM” and “Waveplane-Discrete,” which corresponds to the approaches of using the waveplane-based heuristic algorithm with TDHM and discrete modulation schemes, respectively; (3) “ILP-TDHM” and “ILP-Discrete,” which correspond to the cases of the ILP models under the TDHM-based and discrete modulation schemes, respectively. The ILP model of the discrete modulation scheme is the same as that of the TDHM-based scheme, in which the modulation formats of QPSK and 16 QAM.

The results in Fig. 6 show that the TDHM-based approach can significantly increase the total network transmission capacity by more than 45% compared to the discrete modulation approach that considers the pure QPSK and 16 QAM. This is reasonable since the TDHM-based approach is more flexible in adjusting the spectral efficiency based on the transmission distance of an optical channel. In addition, for both the TDHM and discrete modulation schemes, we also see that the ILP model achieves the best performance in terms of the total transmission capacity. The waveplane-based heuristic algorithm is efficient to perform close to the corresponding ILP model, of which both significantly outperform the simple fixed shortest-path routing and first-fit wavelength assignment algorithm. This is reasonable since the latter uses the shortest (distance-based) paths for lightpath establishment, which can lead to a large number of requests to be blocked. However, in the cases of the ILP model and the waveplane-based heuristic algorithm, we always consider different alternate routes for each request if the shortest route cannot provide sufficient wavelength resources.

We also consider the total satisfied demand units (i.e., end-to-end optical channels) by the different approaches as shown in Fig. 7. Note that the result of satisfied demand units is the same for both the TDHM and discrete modulation schemes. As an upper bound on the satisfied demand units, we provide a curve that counts the total number of requested demand units (i.e., “Total” in legend). Thus, the region between the curve “Total” and any other curve “X” is just the number of blocked demand units for the scheme that the curve “X” corresponds to. We can see that the ILP model has the largest number of satisfied demand units due to its optimality. The waveplane-based algorithm is also very efficient to perform close to the ILP model, while the fixed shortest path scheme performs worst. The reason is similar to the analysis for the total transmission capacity as discussed before.
For the TDHM-based network with SBPP and 1+1 path protection, Fig. 8 compares the maximal achievable network-wide protected capacity (with 100% protection) by different approaches. Note that result for the ILP model in USNET is not shown due to its high computational complexity. We can see that for all the networks, the TDHM-based approach can significantly increase the total network-wide protected capacity, up to 36% compared to the discrete modulation scheme. In addition, we find that SBPP shows a higher network protected capacity than that of 1+1 path protection. This is reasonable since SBPP allows protection capacity sharing among multiple protection lightpaths, while 1+1 does not. Also, we see that the proposed waveplane-based heuristic algorithm can perform close to the ILP model in the n6s9 and SmallNet networks, which therefore verifies the efficiency of the proposed algorithm.

C. Spare Capacity Redundancy

For the TDHM-based network with SBPP protection, we also consider another important performance criterion, i.e., spare capacity redundancy, which is defined as the ratio of the total protection capacity to the total working capacity in the whole network. Fig. 9 shows the spare capacity redundancy of the n6s9 and SmallNet networks for SBPP and 1+1 path protection, in which all the schemes employ the TDHM technique. As expected, SBPP shows a lower spare capacity redundancy than that of 1+1 path protection due to the spare capacity sharing opportunity of the former. Also, we see that the spare capacity redundancies of the ILP model and the heuristic algorithm are close under 1+1 path protection, while under SBPP, relative redundancy difference is larger. This is because the spare capacity sharing feature of SBPP provides more opportunities for the ILP model to carry out optimization, which makes its spare capacity redundancy more optimal than the heuristic algorithm compared to 1+1 path protection.
VI. CONCLUSION

Different from the traditional discrete modulation, the TDHM technique is promising to enable continuous adaptation between the spectral efficiency and the transparent reach of an optical channel. Moreover, as an important advantage, this technique is compatible to the standard ITU-T frequency spacing, which therefore does not require upgrading or changing today’s optical network node architecture. In the context of the RWA problem, we evaluated the benefit of the TDHM technique in increasing the network transmission capacity through the approaches of an ILP model and an efficient waveplane-based heuristic algorithm. The cases with and without network protection were considered, respectively. Simulation studies show that compared to the design based on the traditional discrete modulation, the TDHM-based approach can significantly increase the network transmission capacity. The proposed waveplane-based heuristic algorithm is efficient to perform close to the ILP model, and significantly outperforms other approaches. In addition, the SBPP protection shows a higher protected capacity and a lower spare capacity redundancy compared to 1+1 path protection because of efficient spare capacity sharing by SBPP.

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