Energy Source-Aware Manycast Overlay in WDM Networks

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Abstract—Manycasting is an emerging communication paradigm which allows a single source to reach multiple destinations while providing flexibility in the selection of which destinations to connect with. Traditional wavelength division multiplexed (WDM) networks do not support the all-optical splitting of signals to multiple output ports as required by point-to-multipoint communication schemes. Previous work has proposed an overlay approach known as Manycasting with Drop at Member Node (MA-DMN) to provide manycast support as a logical overlay to basic point-to-point lightpath connections. This approach has been studied extensively and compared to alternative overlay models, and has emerged the obvious candidate for supporting manycast overlays. Throughout its evaluation though, MA-DMN has never been scrutinized in terms of its costs for energy consumption and associated greenhouse gas (GHG) emissions. In this work, we subject MA-DMN to these evaluations, while also proposing a new more energy-conservative emission-aware variant known as MA-DMN using Least Impact Trees (MA-DMN-LIT). We compare these two approaches by simulating realistic quantities of dynamic traffic, and uniformly distributing renewable energy sources to power nodes throughout the network. We find that MA-DMN-LIT reduces energy consumption over MA-DMN by 6-10% across the network, while also reducing CO₂ emissions by as much as 27%. We further conclude that MA-DMN-LIT also provides lower connection blocking by not over-subscribing shorter paths in the network as its emission-blind counterpart does.

Index Terms—Manycasting, Green, Emissions, WDM, Overlay, Split-Incapable.

I. INTRODUCTION

Large-scale science collaboration and workload distribution is increasing rapidly. Rarely does a single laboratory conduct experiments, perform calculations and computations on the experimental data, analyze and interpret those results, and test the validity of the conclusions drawn from the result analysis. As the magnitude of experimental data yield soars into the arena of petabytes and exabytes of information, local workstations with spreadsheets of data are becoming ever-obsolete. Current trends see experiments performed at one centralized site, with the data generated by that site transferred to various super-computing sites for independent analysis. The analyzed data is then likely duplicated and copied to colleagues and peers who aim to draw their own conclusions of the data, as well as the analysis of competing or cooperating parties. As the turnaround time for result analysis and experimental calibration decreases, the need to distribute information across a network to make use of multiple parallel resources becomes obvious. Such scenarios showcase the necessity of new point-to-multipoint distribution paradigms like multicasting and manycasting.

Multicast communication establishes connections from a single source, i.e. experiment laboratory, to multiple destinations, i.e. super-computing sites, data analysis laboratories, or super-storage facilities. If one such destination cannot be used, or is unreachable given the current network or resource state (too much competing traffic, prior computational commitments), the overall distribution task is futile. Like multicasting, manycasting [1] allows connections to be established from a single source to multiple destinations, however not all candidate destinations must be reached for successful provisioning. In manycast, the actual destinations covered are to be determined as a subset of all the candidates, instead of being given a priori as in multicast [2]. This subset may prioritize certain sites based on cost or end-to-end delay, or if the destination resources are homogenous, the subset may merely specify that some number of the candidates must be reached regardless of their cost/location. From their respective definitions, manycasting can be interpreted as a generalization of multicasting.

The advantages of supporting point-to-multipoint communication paradigms in the optical layer have been discussed in [3], [4]. The manycast provisioning problem has been shown to be NP-hard in [5]. In [6], we address supporting manycast communication at the optical layer and propose heuristics and integer linear programs (ILPs) to solve the routing and wavelength assignment problem of static manycast traffic demands. In all of these referenced works, it is assumed that manycasting is supported by creating light-trees [7].

Our prior works [8], [9] visit the manycast provisioning problem in split-incapable networks, such as the DOE’s Energy Sciences network (ESnet) that do not support optical splitting in the OXCs and are therefore limited to unicast circuits at the optical layer. These works consider logical overlay approaches to building manycast trees in both static and dynamic traffic environments as both optimal (ILP) and approximate (heuristic) solutions on WDM networks. In this work, we present an evaluation of these proposed approaches from the perspective of both energy consumption and green-

1This work has been supported by the Department of Energy (DOE) COMMON project under grant DE-SC0004909.

2A light-tree is a generalization of a lightpath that starts at the source node of a manycast request and reaches all of its destinations all-optically by possibly branching (splitting the signal) at intermediate nodes.
house gas emissions in dynamic traffic scenarios on real-world networks.

In [10] the authors present a broad overview of early efforts in saving energy in network operations. Energy efficient routing schemes, network planning, and selectively turning equipment on and off are mentioned as strategies to reduce energy consumption. One strategy to make the network green, or lower the produced greenhouse gas (GHG) emissions caused by the network is to co-locate data centers and Grid resources close to sites with high availability of renewable energy resources, i.e. wind, solar, geothermal. The trade-off between rise in transport emissions and reduction through this green processing is analyzed in [11]. The authors propose anycast selection of processing data-centers according to which data-center can be reached in the most energy-efficient way.\(^3\)

Recently research interest has risen for the consideration of renewable energy sources in routing and network planning: [12], [13], [14], [15]. These efforts marry the advantages of green data processing and green data transport. The authors of [16] present one of the first approaches that makes use of dual power sources (clean renewable vs. fossil fuels) for routing and wavelength assignment. Unicast routing is optimized in terms of emissions yield on this partially green network. We have previously presented work on dual power source-aware algorithms for network survivability in [17].

The rest of the paper is organized as follows: In Section II we summarize the proposed manycast overlay heuristics and compare them qualitatively. Section III introduces the node model used in evaluating the overlay approaches and provides formulas for evaluating the power consumption, energy consumption, and emissions of network nodes based on the proposed model. We present results of simulated dynamic manycast traffic on real networks in Section IV, and finally conclude the paper in Section V.

II. OVERLAY APPROACHES

In this section we present the manycast overlay models for split-incapable networks as proposed in our previous studies [8], [9] and present an illustrative example of the differences between them. Further, we qualitatively summarize the relevant comparisons between the proposed models. We also propose a novel, emission-aware variation on the preferred algorithm, which aims to minimize the overall GHG emissions yield for a set of manycast requests.

Given a network \( G = (V, E) \), a manycast request can be defined as \( R = (s, D, K') \) where \( s \) is the source node of the request \((s \in V)\) and \( D \) is the set of candidate destination members (nodes) \((D \in V - \{s\})\). For a manycast request with \( K \) destination members, we represent the destination set as \( D_r = \{d_1, d_2, \ldots, d_K\} \), \( K' \leq K \) is the number of nodes necessary to reach in order to service the manycast request. Note that if \( K' = K \), the manycast request is specifically a multicast one. Collectively, we will refer to \( s \) and \( D \) as the members of a manycast request. To service a given manycast request we must find a set of lightpaths (combination of a route and a wavelength) that starts at the source node of the request and reaches at least \( K' \) nodes from the candidate destination set in the overlay network. We assume that the wavelength continuity constraint is enforced for all overlay models.\(^4\)

A. Single-Hop Overlay Model

The first proposed model is a single-hop overlay that establishes individual lightpaths from the source node, \( s \), to each of the selected \( K' \) destinations from \( D_r \). This single-hop model is referred to as \textit{Manycast via WDM Unicast (MA-VWU)}. In the worst-case, it’s possible that these individual lightpaths may overlap on some physical links, thus consuming excess bandwidth unnecessarily. The authors of [18] predict the inevitable growth and complexity of next generation applications will render such a naïve manycast overlay mechanism inefficient and infeasible due to this high bandwidth consumption.

B. Multiple-Hop Overlay Model

Since the MA-VWU model is exceedingly wasteful, we have proposed an alternative multiple-hop logical overlay called \textit{Manycasting with Drop at Member Node (MA-DMN)}, wherein a set of lightpath routes is established which connect the source node, \( s \), to the selected \( K' \) destinations from \( D_r \), such that not all lightpaths must be directly sourced at \( s \). The MA-DMN approach allows lightpaths to be terminated (dropped to the electronic layer) or originate exclusively at member nodes of the manycast request, thereby establishing manycast trees in the overlay layer consisting of (possibly) multiple hops from the source. Each drop-member node

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\(^3\)Anycasting is a specialized case of manycasting that must reach exactly one candidate destination.

\(^4\)A lightpath uses the same wavelength on all the physical links of the network it traverses.
The heuristic used to satisfy multiple-hop manycast overlay trees is reviewed in detail in [8]. For a manycast request to satisfy the request, the referenced algorithm establishes consumption and thus request blocking than MA-DMN. Previous study has shown a single tree for each manycast request, such that the first hop is to the nearest node. To satisfy request \( R_1 \), we can create a set of lightpath routes as follows: a lightpath from node 1 terminating at node 2, and another lightpath originating from node 2 reaching node 5. Notice that since node 2 is a destination member of the manycast request, we can drop a lightpath at this node. Similarly for request \( R_2 \), we can create lightpath routes from node 4 to node 5 and from node 5 to node 2. To service the manycast requests, MA-DMN utilizes only a single wavelength as compared to the two wavelengths needed for the MA-VWU model. This decrease in the number of wavelengths comes at the expense of an increase in the average number of logical hops (two for MA-DMN, and just one for MA-VWU). Corresponding logical views are depicted in Fig. 1(c) and (d).

D. Emission-Aware Overlay Variant

Both the MA-VWU and MA-DMN overlay approaches are blind to energy consumed and the emissions produced by their resulting manycast overlay tree solutions. Here we propose a novel emission-aware variant of MA-DMN named \textit{M}anycasting \textit{w}ith \textit{D}rop at \textit{M}ember \textit{N}ode \textit{u}sing \textit{L}east-Impact \textit{T}rees (\textit{MA-DMN-LIT}). Like MA-DMN, this approach still produces \( K \)-alternate trees for each manycast request, but rather than greedily selecting the tree which adds the fewest wavelengths to the network, MA-DMN-LIT will inspect the emissions potentially produced by each tree and provision the one with the least immediate impact in this regard. If multiple trees should produce the same emissions, the approach simplifies down to the MA-DMN algorithm and breaks the tie based on resource consumption. We present a comparative analysis of this emission-aware approach and its emission-blind counterpart in Section IV.\textsuperscript{6}

Algorithm 1 describes the MA-DMN-LIT tree creation and selection process. This algorithm is a modified version of the MA-DMN algorithm found in [8]. Just as MA-DMN does, the algorithm generates \( K \) candidate trees, with the constraint that the first hop in the \( k \)-th tree is the shortest path from the source node to the \( k \)-th candidate destination of the manycast request. The differences from MA-DMN are found at lines 14 and 16 of Algorithm 1. Once the candidate trees have been constructed, their GHG emissions are evaluated, using Eqs. (1) – (8) described later in Section III-B. The worst-case runtime complexity for this operation is the amount of time it takes to sum up the emissions at each node in the tree, \( O(|V|) \). Once all the candidate trees have been constructed and

\begin{algorithm}
\textbf{Algorithm 1: MA-DMN using Least Impact Trees}
\begin{algorithmic}[1]
\State \textbf{input:} Manycast Request: \( R = (s_i, D_i, K_i) \), \( D_i = \{d_1, d_2, \ldots, d_K\} \)
\State \textbf{output:} Manycast overlay tree producing the lowest GHG emissions
\State \( AltTrees[K] = \text{NULL} \)
\State \( routedDestinations = 0 \)
\State sort(routeList)
\For {each \( d_i \in D_i \)}
\State \( Tree_k = \text{NULL} \)
\State \( Tree_k.add(SP(s, d_i)) \)
\State update routedDestinations
\For {each route \( r_i \in \text{routeList} \)}
\If {\( \text{routedDestinations} \geq K' \)}
\State break
\EndIf
\EndFor
\State calculateEmissions(AltTrees)
\State sortByEmissions(AltTrees)
\State return min(AltTrees)
\EndFor
\end{algorithmic}
\end{algorithm}

\textsuperscript{5}We have also compared these models in terms of energy- and emissions-efficiency, but omit the results because as expected, MA-VWU is too wasteful of resources to yield emissions comparable to MA-DMN.

\textsuperscript{6}We have also evaluated an emission-aware variant of MA-VWU which selects the destinations with the greenest routes from the source, but omit those results due to space restrictions.
TABLE I
Node-Specific Variables

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{IN}$</td>
<td>Input traffic from access network</td>
<td>Gbps</td>
</tr>
<tr>
<td>$A_{OUT}$</td>
<td>Output traffic to access network</td>
<td>Gbps</td>
</tr>
<tr>
<td>$L_D$</td>
<td>Lightpaths dropped from WDM to IP (O-E)</td>
<td>integer</td>
</tr>
<tr>
<td>$L_A$</td>
<td>Lightpaths added to WDM from IP (E-O)</td>
<td>integer</td>
</tr>
<tr>
<td>$L_{IN}$</td>
<td>Incoming lightpaths</td>
<td>integer</td>
</tr>
<tr>
<td>$L_{OUT}$</td>
<td>Outgoing lightpaths</td>
<td>integer</td>
</tr>
<tr>
<td>$\epsilon_n$</td>
<td>Node-specific emission-factor</td>
<td>kgCO$_2$/kWh</td>
</tr>
</tbody>
</table>

TABLE II
Network-Specific Variables [19]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>Transponder transmission rate</td>
<td>10</td>
<td>Gbps</td>
</tr>
<tr>
<td>$\pi_{TX}(r)$</td>
<td>Transponder’s O-E-O power consumption</td>
<td>0.05</td>
<td>kW</td>
</tr>
<tr>
<td>$\pi_{OXC}$</td>
<td>OXC power consumption on optical plane</td>
<td>0.1</td>
<td>kW</td>
</tr>
<tr>
<td>$\pi_{IP}$</td>
<td>IP layer power consumption</td>
<td>0.01</td>
<td>kW/Gbps</td>
</tr>
</tbody>
</table>

Eqs. (1) – (4) provide relationships between the values in Tables I and II and their respective effects on nodespecific power consumption. For simplicity, Eqs. (1) – (3) assume that all operands are in terms of an instant of time, i.e., $p_{IP}$ is more accurately described as $p_{IP}(n,t)$, where $n$ is the node in question, and $t$ is the instant in time of this calculation. In Eq. (3), $\alpha = 0.085$ kW is the power consumed by amplifiers, which are necessary even for all-optical bypassing of a lightpath through a node. The value to zero [20]. The average $\epsilon_n$ for the US was .665 in 2009 according to the Environmental Protection Agency.\footnote{http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html}

III. Nodal Power Consumption Model

Here we describe the node model used in evaluating the overlay heuristics described in the previous section. We also present values and formulas for calculating power consumption, energy consumption, and emissions generated by each node in the network. In [19] the authors propose a comprehensive model for multilayer network power consumption which we use as foundation and combine with [20] to calculate GHG emissions. Fig. 2(a) presents an illustration of a generalized node, which can be specialized as an OXC, ROADM, etc. This model can be used to identify the power consumed by any heterogeneous node in the network based on its classification in terms of its role in satisfying a manycast overlay request, as well as its incoming and outgoing nodal degrees. The model illustrates not only the optical layer, but also the IP layer and the ingress/egress points to the access network. The component in Fig. 2(a) labeled “Transponder” represents the transmitter/receiver component of the switch on the optical plane. Table I describes the vector labels in Fig. 2(a), and provides their units of measurement.

The table also includes an emission-factor value, $\epsilon_n$ that represents the impact of power consumption on GHG emissions. The units for the emission-factor are kilograms of carbon dioxide equivalent per kiloWatt-hour (kgCO$_2$/kWh). For simplicity, we consider heterogeneous networks consisting of two distinct types of nodes classified by their energy sources. Nodes powered by fossil fuels are referred to as black nodes and are assigned an $\epsilon_n$ value of 1 kgCO$_2$/kWh. This value means that for each kW of power consumed by the node, one kg of CO$_2$ is emitted per hour. Network nodes powered exclusively by renewable energy sources are dubbed green nodes, and are awarded an emission-factor of 0.01 kgCO$_2$/kWh, which indicates they are cleaner than black nodes and may consume more power with a very small adverse environmental effect. Green nodes are not completely free of emissions however, and thus $\epsilon_n$ may not be set equal

evaluated, they are then sorted according to their total GHG emissions, an operation which runs with a complexity of $O(K)$. Finally, the lowest-emissions tree is selected and provisioned on the network to satisfy the manycast request. The overall complexity of the MA-DMN-LIT algorithm can be represented by the product of the number of routes traversed in routeList, $O(|V|^2)$, and the maximum number of nodes to traverse in a single tree, $O(|V|)$ for each of the $K$ trees: $O(K|V|^3)$.

A. Manycast Tree Nodal Classification

The given node model is uniform across all nodes in the network, both green and black, however the power and energy consumed by each node is unique depending on its role in provisioning a manycast overlay tree. Table III depicts the mutually exclusive types that each network node may be classified as for an individual manycast request by MA-DMN and MA-DMN-LIT. Nodes which are not destination members, but may be found along paths within the tree are intermediate nodes. The switches at these nodes do not require any electronic conversion, thus signals may bypass them all-optically, incurring only very minor power and energy costs. Source nodes and destination nodes are responsible for performing E-O and O-E conversions respectively, which consume far more power than an intermediate bypass node. Destination nodes that not only terminate a lightpath but also serve as the source for a connecting lightpath are defined as drop-members of the tree, and incur additional energy costs for splitting the signal electronically to be forwarded along separate lightpaths to one or more additional destination nodes. Unused nodes are those which are not included in the tree solution for provisioning a manycast request and therefore do not consume any power or energy for the given request. If a node is unused across all currently provisioned manycast overlay trees, the node is non-essential to the network and may be switched off to conserve energy and prevent idling costs. All network nodes are idle before any requests arrive and again after all requests have departed (i.e. lightpaths freed) in dynamic traffic scenarios.

B. GHG Emissions Formulas

Eqs. (1) – (4) provide relationships between the values in Tables I and II and their respective effects on node-specific power consumption. For simplicity, Eqs. (1) – (3) assume that all operands are in terms of an instant of time, i.e., $p_{IP}$ is more accurately described as $p_{IP}(n,t)$, where $n$ is the node in question, and $t$ is the instant in time of this calculation. In Eq. (3), $\alpha = 0.085$ kW is the power consumed by amplifiers, which are necessary even for the all-optical bypassing of a lightpath through a node. The value
TABLE III
OVERLAY NODE CLASSIFICATION

<table>
<thead>
<tr>
<th>Class</th>
<th>Indegree</th>
<th>Outdegree</th>
<th>Qualifying Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source</td>
<td>0</td>
<td>([1, K'])</td>
<td>-</td>
</tr>
<tr>
<td>Destination</td>
<td>1</td>
<td>0</td>
<td>Request Member</td>
</tr>
<tr>
<td>Intermediate</td>
<td>([1, K'])</td>
<td>([1, K'])</td>
<td>Request Non-Membr; In = Out</td>
</tr>
<tr>
<td>Drop-Member</td>
<td>1</td>
<td>([1, K'-1])</td>
<td>Request Member</td>
</tr>
<tr>
<td>Unused</td>
<td>0</td>
<td>0</td>
<td>Not in Tree</td>
</tr>
</tbody>
</table>

\(\beta = 0.15 \text{ kW}\) is the constant power consumed for directing the lightpaths to the appropriate ports, for example using microelectromechanical systems (MEMS). Eq. (4) describes the total power consumption for a node at an instant of time as the sum of the power consumed at the optical, IP, and access layers. Eqs. (5) and (6) calculate the node-specific and network-wide energy consumption respectively over the total time interval of request arrivals and departures. Eqs. (7) and (8) calculate the node-specific and network-wide GHG emissions respectively. We use these formulas as the basis by which to obtain the results presented in Section IV and to compare the relative energy- and emission-efficiency of MA-DMN and MA-DMN-LIT.

\[
p_{IP} = \pi_{IP}(A_{IN} + A_{OUT} + r(L_D + L_A)), \tag{1}
\]

\[
p_{OEO} = \pi_{OEO}(r(L_D + L_A)). \tag{2}
\]

\[
p_{WDM} = \pi_{WDM}(L_D + L_A) + \alpha(L_{IN} + L_{OUT}) + \beta. \tag{3}
\]

\[
p(n, t) = p_{IP} + p_{OEO} + p_{WDM}. \tag{4}
\]

\[
\phi_n = \int_{t_0}^{T} p(n, t) \, dt. \tag{5}
\]

\[
\Phi = \sum_{n} \phi_n. \tag{6}
\]

\[
\gamma_n = \int_{t_0}^{T} p(n, t) \cdot \epsilon_n \, dt. \tag{7}
\]

\[
\Gamma = \sum_{n} \gamma_n. \tag{8}
\]

Consider the overlay tree shown in Fig. 2(b), which may be a solution provided by MA-DMN for the manycast request, \(R = (A, \{B, C, D\}, 3)\). According to the classifications presented in Table III, node \(B\) may be classified as a drop-member. Fig. 2(a) depicts the internal state of node \(B\) according to the described model. The number of lightpaths into the node, \(L_{IN}\), is equal to 1, and that is the lightpath directed from node \(A\). Since this node is a drop-member, the incoming signal must be considered at the IP level as well. The signal therefore passes through the photonic transponder device for the incoming lightpath’s selected wavelength, in essence dropping the signal to the electronic layer, completing an O-E conversion. Thus, \(L_D = 1\). In the node’s IP switch, the signal is split electronically into multiple disparate signals. Since node \(B\) is in fact a reached destination of the request, one of these split signals must be passed to the access network and directed to its desired host. Therefore, assuming each incoming lightpath consumes an entire wavelength, the value of \(A_{OUT}\) will be increased by the outgoing signal’s bandwidth, 10 Gbps. The other two signals, shown in Fig. 2(a) with a dotted and dashed line, represent the signals which will be sent to the other two destination nodes \(C\) and \(D\), respectively. The signals must each be passed back to the optical plane and sent along a lightpath, thereby invoking two separate E-O conversions, and resulting in an \(L_A\) value of 2. The two signals are then forwarded to their respective destinations along their own lightpaths, completing the utilization of node \(B\), and resulting in \(L_{OUT} = 2\). In this particular example, no traffic arrives from the access network, so \(A_{IN} = 0\) Gbps. All the values necessary to compute node \(B\)’s consumed power and energy using Eqs. (1) – (6) are now known.

IV. PERFORMANCE EVALUATION

In this section we subject both the emission-blind and the emission-aware overlay approaches to various network scenarios and evaluate their relative performances. Each set of manycast requests consists of \(10^5\) requests. Manycast requests arrive according to a Poisson process with average arrival rate \(\lambda\) and exponentially distributed holding times with an average service rate \(\mu\). The network load in Erlangs is calculated as the ratio of the average arrival rate to the average service rate \((\lambda/\mu)\). The source node of each manycast request is uniformly distributed. For each request, the size of the candidate destination set \((K)\) is uniformly distributed from 3 to \(D_{max}\) (a parameter that represents the maximum number of candidate destination nodes). For a particular manycast request \(R_r\), with \(|D_{R_r}| = K\), the minimum number of destination nodes \((K')\) to reach in order to satisfy the request is set to \(\lceil K/T \rceil\). The results presented in this section represent the average of 30 unique request sets. For each request set, the percentage of green nodes and black nodes throughout the network is fixed.
however nodes are uniformly selected to be green. In what follows, we present the results for the augmented EnergyScience core science data network (ESnet) shown in Fig. 4 for $D_{\text{max}} = 10$ and number of wavelengths per link, $W = 16$.9 Requests are assumed to require bandwidth granularity of exactly one wavelength on established lightpaths.

Fig. 3(a) shows the relative blocking performance of MA-DMN and MA-DMN-LIT. Recall that MA-DMN selects trees based on their impact on the network’s usage of wavelength resources, likely taking many small trees consisting of short unicast paths in quick succession. This prevents many larger requests with longer distances between destinations from finding appropriate resource availability to be successfully provisioned. Even when no green nodes are introduced to the network the result is higher blocking than the MA-DMN-LIT approach, which aims to find the “greenest” trees irrespective of their size. The reason for this is that even though MA-DMN-LIT will pick longer trees frequently, fewer network links are consumed by several small tree solutions in quick succession. Essentially, by spreading the consumption of links across the network and using trees with more drop-members in them, fewer links are consumed at any given time, allowing for future requests to use the remaining resources. For 50% green node distribution, MA-DMN performs identically since it is emission-blind, but MA-DMN-LIT performs just slightly worse than previously. More requests are blocked because as more green nodes are introduced, longer paths are incentivized. Instead of simply selecting longer paths on occasion, the heuristic is now likely to pick them more often to reach the green nodes along them. This assessment is supported by Fig. 3(b), which shows the physical route size, in number of hops on provisioned trees.

Fig. 3(b) also provides a clearer picture of the shape of overlay trees provisioned within the network. The figure depicts the average logical hop count of provisioned overlay trees. MA-DMN-LIT establishes trees with more drop-members than MA-DMN. So while MA-DMN is focused on picking trees that don’t over-consume available wavelengths, MA-DMN-LIT selects trees that have fewer outgoing branching points from their drop-nodes. As is evident from Eqs. (1)−(4), nodes which require O-E-O conversions are the most expensive in terms of power consumption. Nodes which must electronically split incoming signals to multiple output ports electronically consume even more power. Therefore, in terms of power consumption and ultimately energy consumption, those trees which use drop-members as splitting points are more expensive than those that use them simply as straightforward drop points. Obviously though, in order for those trees with fewer splitting points to reach the requisite $K'$ destinations, they must incur the cost of more logical hops. This is evident from Fig. 3(b) in that the emission-aware overlay approach chooses paths with more logical hops than the emission-blind approach.

Fig. 3(c) depicts the total energy consumed in the network when normalized with each heuristic’s blocking probability with 0% and 50% distribution of green nodes. Unsurprisingly, the energy consumed by MA-DMN is identical for both distribution patterns. Recall that the blocking rate of MA-DMN-LIT rises slightly as more green nodes are introduced, incentivizing
longer path selections, but consuming more resources greedily. This slight increase in longer paths directly correlates to the slight increase in energy consumed by the heuristic when introduced to a wider distribution of green nodes. Longer paths inherently consume more energy, but MA-DMN-LIT may sacrifice energy savings in an effort to ensure that that energy is coming from renewable sources. However, MA-DMN-LIT maintains its energy savings over MA-DMN by 8 − 10% at 0% green distribution, and 6 − 10% at 50% green distribution.

Corresponding GHG emissions, normalized with blocking probability, are given in Fig. 5. Regardless of nodal distribution, MA-DMN-LIT utilizes green resources more responsibly than its emission-blind counterpart. With all network nodes powered by carbon-based fuel sources, MA-DMN-LIT reduces its produced emissions by 8 − 12% over MA-DMN across the shown arrival rates. When half the network is fueled by clean-energy, this improvement is nearly doubled, with MA-DMN producing 10 − 27% more emissions than its emission-aware alternative. When 50% of the nodes are powered by renewable energy sources, the overall emissions are obviously lower than they would be if all nodes were carbon-supplied, but should approach the network’s inherent 50% reduction. Both algorithms make efficient use of the low-emissions availability. The MA-DMN heuristic reduces its total emissions by between 43% and 58% across all traffic arrival rates. The MA-DMN-LIT heuristic performs even better, with an overall reduction in GHG emissions of 48 − 65%. These savings are equivalent to approximately 50 metric tons of CO₂.

V. CONCLUSION

Despite the increasing popularity of, and awareness toward the manycast communication paradigm, not all networks have begun to support equipment which would allow them to fully utilize the flexibility that the approach can offer. Many networks still only support point-to-point communication schemes, relegating point-to-multipoint enhancements to a logical overlay implementation. Previous work has proposed the MA-DMN overlay approach and a corresponding, efficient heuristic with which to compose tree solutions to manycast connection requests by stitching together unicast lightpaths in a logical manner. Until now, this approach has not been considered in terms of energy-efficiency and its impact on GHG emissions production. In this work, using an advanced node model with which to investigate the effects of establishing overlay trees on carbon-fueled and renewable energy-fueled network devices, we have concluded that not only can the MA-DMN algorithm connection blocking be lowered, but its emissions output can also be reduced through simple modification. We have developed the emission-aware MA-DMN-LIT variant to select only low-emissions trees to provision manycast requests, and through extensive simulation, have showcased its improvements relative to the emission-blind MA-DMN. The implications discussed here lend credence to the notion that networks can be both reliable, scalable, and clean. Areas of future investigation include variable emission-factors for nodes to represent different types and availability of energy sources, e.g. solar power may have different costs in certain geographical locations than another source like wind power. At a certain time of the day or year, the ratio of available renewable and non-renewable sources may vary, affecting the greenness of various nodes throughout the network. We aim to investigate how this variability affects the performance of our heuristics.

REFERENCES