COST-OPTIMIZED SINGLE MODE SDM SUBMARINE SYSTEMS

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Abstract: Optical submarine cable systems face a paradigm shift as both capacity demand and cost-per-bit pressure require use of multiple spatial dimensions or Space Division Multiplexing (SDM). The most practical first step in this direction is to continue using single mode fiber technology while adapting it to fit the SDM design principle: transmitting more information through more parallel paths within the limit of the available electrical power. It is important to accurately predict future cost-optimal solutions that maximize capacity and improve cost-per-bit while minimizing risks associated with introduction of the new approach.
Finding cost optimal solutions requires a model that accounts for both physical and economic aspects of all system elements. The physical aspects include mechanical, electrical and optical properties, while economic aspects can include costs. The model should accurately represent both today's system elements and SDM versions of future system elements. For example, the cable model should be scalable to accept different numbers of fibers, changes in conductivity, and reflect corresponding changes in the cost of the cable. Without that, overall cost/bit optimization of future SDM systems becomes inaccurate.
In this work we describe the results of the physical-economic model optimization. We show that a 32-fiber solution (or 16 fiber pair solution) is close to optimal for next generation SDM systems, and that exceeding 32 fibers per cable has diminishing return. We discuss the difference between cost-per-bit optimum of a wet-plant, versus the cost-per-bit optimum of the whole system, including line terminals. We also investigate the requirements for "SDM transponders" such as spectral efficiency and nonlinear compensation.

1. INTRODUCTION

The demand for submarine connectivity continues to grow, while advances in single mode transmission and modem technologies are saturating, and near future single mode fiber capacity improvements are not expected to be significant. There seems to be an industry agreement that future cable capacity growth is possible mostly due to increase of the number of parallel paths or space division multiplexing (SDM). Submarine systems also have practical limitation of power supply, since electrical power is delivered to submarine amplifiers from the shores. Meeting the growing submarine capacity demand is a challenging task, since both capacity and power efficiency of the system must be improved while controlling the overall system costs.

It has been noticed [1] that transmission at lower spectral efficiency (SE) per spatial path of an SDM system may improve power efficiency. Therefore, one can grow overall system capacity by increasing the number of paths while keeping overall power consumption constant [2]. Experimental demonstration of this principle can be found in [3], while discussion of capacity increase under limited power supply in submarine systems can be found in [4, 5]. It has been shown [6] that there is a fundamental limit in power efficiency for an SDM system. Once this limit is reached further capacity increase becomes possible only through improvements in power delivery, for example; through cable voltage increase or lowering cable resistance. Practical limitations on cable voltage are discussed in [2, 7]. Designing large capacity submarine systems can lead to unmanageably large and expensive solutions. Optimal design is possible with the use of a model combining both the physics and economics of the system, such as in [8].

In this work we first discuss the interplay between power efficiency and cost efficiency. Then we discuss the interaction of component costs with system design and how they are included in our physical-economic model. We focus on SDM systems based on single mode fibers (SMFs) since submarine links will likely be using SMFs for quite some time. Particular attention is paid to the cable design, since the cable cost accommodating different number of fibers can vary noticeably and impact the results. This contrasts with [8] where interaction between cable design, cable conductivity and costs are not accounted for. Finally, we present results of the model for optimally designed future submarine systems.

2. POWER AND COST EFFICIENCIES

We define power efficiency as the ratio of capacity to available power in the system. An important property is the existence of optimal spectrum efficiency [6, 9]. This optimum is the result of the effect known as “signal droop”, which is displacement of a portion of signal by ASE when amplifiers work in a saturated regime. There is a natural question: *Does signal droop and the existence of optimal power efficiency play any role in the choice of the most cost-efficient system?* To answer this question, we introduce cost efficiency or cost-per-capacity coefficient c_C as a ratio of the system cost c to the total system capacity C:

$$c_C = \frac{c}{C} \qquad (1)$$

We define power efficiency (PE) as ratio of the total capacity to the total power P:

$$PE = \frac{C}{P} \qquad (2)$$

We notice that for the same total available power, cost-per-capacity is proportional to cost divided by power efficiency:

$$c_C \sim \frac{c}{PE}\bigg|_{\text{fixed P}} \qquad (3)$$

Let us consider an extreme example where the costs of the transponders, amplifiers and fibers are negligibly small compared to the cost of the rest of the system, which include the costs of the rest of the cable, system installation, permitting, marine operations etc. This situation is not unimaginable in the future, assuming that the price reduction trajectory of the transponders, amplifiers and fibers is much faster than that of the other cost items. In this extreme example, the cost of the system is minimized when the power efficiency term PE in Eq. 3 is maximized. That is, the most cost-efficient system is the one which operates at power efficiency maximum. Therefore, the answer to the question above is yes, the signal droop and power efficiency *defines* the most cost-efficient point in this example.

In a closer to life example, we can consider 14,000 km link with 70 km repeater spacing. We use typical cable costs, fiber costs, cable lay costs and amplifier costs inside the repeater bottle. We keep the total optical power at the output of a repeater across all fibers the same, evenly distributing it between a variable number of spatial paths. Costs are only modified due to variation of the number of fibers and the number of amplifiers in the system in this example. We ignore the cost of the modems in this example for simplicity. For capacity estimation we can perform calculations similar to [6, 9], for which we can assume that the amplifier NF and bandwidth stays the same and that the amplifiers are in saturation regime, that is the sum of total ASE power and signal power at the output of each amplifier is the same for all amplifiers in the link. Finally, cost per capacity can be found as ratio of the costs to system capacity estimation, per Eq. 1.

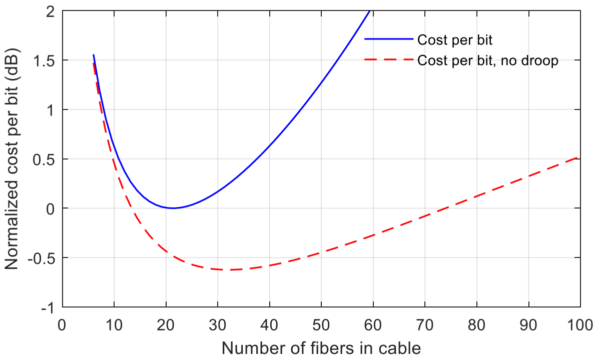

Figure 1: Cost per capacity dependence with and without inclusion of signal droop for a 14Mm cable.

Figure 1 shows the result of these calculations where two cases are considered: with and without signal droop inclusion. To remind, signal droop inclusion defines a PE optimum. As one can see, there is significant difference in both the value of minimal cost-per-capacity and of the number of fibers required to achieve this minimum. Therefore, while PE optimum does not define the cost-per-capacity minimum, it clearly has an impact. Similar analysis in [8] does not include this effect.

Despite the simplicity of the above examples, they also demonstrate limitations of such approaches. For example, the assumption that a cable that can fit 50 fibers and a cable that can fit 20 fibers costs the same is not realistic. Another example of such assumption is fixed conductivity of the cable, that is not optimized/changed when different number of fibers or different system lengths are considered. We have developed a detailed SDM model that is not limited by those assumptions.

3. NUMERICAL SDM MODEL

Our model of an SDM system is comprised of blocks or sub-models for each of the system component. Figure 2 shows the overall high-level structure of the model.

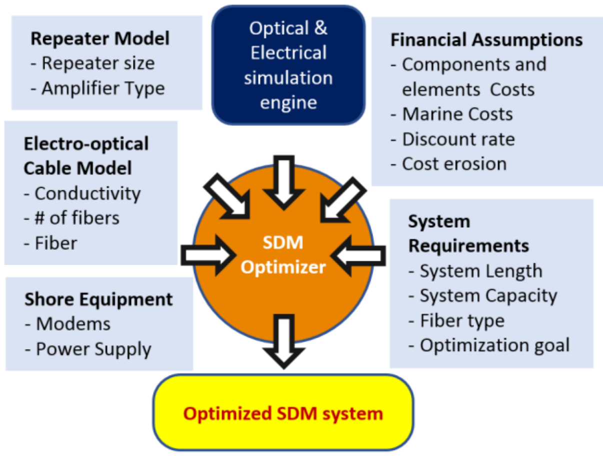

Figure 2: Block diagram of the simulation tool

Many interdependencies exist in this model. Cable conductivity, power feed equipment (PFE) voltage and repeater spacing define the maximum possible number of pumps in a repeater. The number of pumps together with the SDM index (number of fibers per pump) defines the number of parallel paths or fibers and the number of EDFAs. The number of EDFAs define the repeater bottle size and the need of multiple bottles. When the number of fibers does not fit into this particular cable, the cable is redesigned, which may change cable conductivity. That in turn affects the maximum possible number of pumps in the repeater. All of these properties have impact on costs. Here, we describe the most important approaches for this model and show the result of optimization.

The cable model accurately represents existing cable structure with copper being the main conductor. In this paper we focus only on copper, because the main conclusions do not depend on the choice of the conductive material. Fibers are enclosed in a loose tube, which is surrounded by a strength wire structure. The conductor tube is swaged around the strength wires and covered by a layer of an insulator. The number of fibers a given cable can fit directly affects the wire structure size and the copper tube diameter. The copper tube thickness has its own boundaries, which results in dependence of cable conductivity and costs on the number of fibers the cable can support.

We assume realistic costs and performance of all system elements based on today's and near future technology. This includes modems, which operate approximately 6dB away from the Shannon limit. This number includes both transponder performance and margins typically allocated for various purposes, such as manufacturing, operation and aging. Power delivery to the submarine repeaters is optimized in all cases by adjusting repeater voltage to get the maximum power to the repeater. All efficiencies of electrical equipment inside repeaters are accounted for, together with the cost information. Maximum cable voltage is assumed to be 15KV for a single-end-feed powering case.

For SDM index definition and cost calculation, we assume 800mW pumps. The SDM index is defined as a ratio of the number of fibers served by a single pump. The actual simulated topology is "two pumping N," where 2 pumps are combined into a pump unit using a coupler and then split through the network of splitters to pump N EDFAs. This is done for redundancy reasons. All costs and losses are accounted for. This topology is schematically shown in Figure 3 below.

Simulation of signal propagation is based on GN model [10] with nonlinear compensation coefficient when the impact of nonlinear compensation is tested. The linear portion (ASE) is calculated based on amplifier NF and losses in the system.

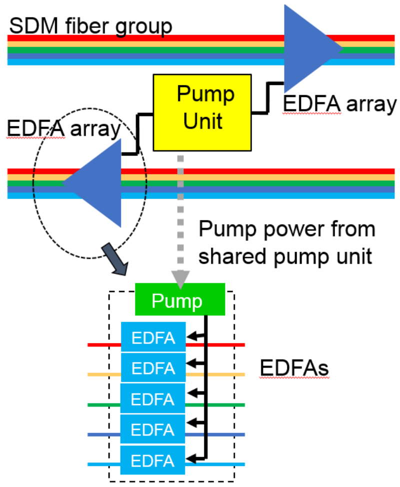

Figure 3: Assumed topology in the tool

The model uses a multidimensional optimization routine to find optima. We construct a merit function or optimization goal. The goal could be the wet-plant cost, the whole system cost (that includes everything, including shore equipment and SLTE), the whole system cost without line-cards or modems, etc. Usually we use capacity and system length as targets and optimize other parameters to achieve the minimum costs. Those other parameters can include repeater spacing, PFE voltage (with a limit), SDM index, cable resistance (with limits imposed by cable design), and the system or amplifier bandwidth (with a limit). Often the bandwidth is excluded from the optimization due to the tendency of the optimizer to always converge to the largest bandwidth available.

4. RESULTS AND DISCUSSIONS

Most of our simulation results are presented as contour plots of some parameter (system cost for example), where the horizontal axis is system length and vertical axis is capacity. It is important to understand that for each point of this 2D contour plot, all parameters of the system are optimized to achieve the minimal cost for that system at that distance and that capacity. Those parameters include cable design parameters as well such factors as cable size, conductor thickness etc.

We define SDM benefit as the ratio of the cost of the “conventional” system to the cost of a fully optimized SDM system for the same capacity. The system cost includes all costs associated with the system, including terminals, modems, installation costs, permitting, etc. The conventional system is defined with “2 pumping 2” topology and operates at the maximum SNR performance. The fully optimized system has a variable SDM index and the system is not at the peak of the nonlinear performance.

The cable can be always designed to fit the necessary amount of fibers and no more. This created a problem for conventional systems: the cable becomes too thin to support the required conductivity for longer system lengths. If for longer distances the cable is designed to be able to fit larger number of fibers than required, then the cable becomes more expensive and the wet-plant (i.e. cable + repeater) cost becomes 5 to 16% more expensive than for SDM systems for the majority of the considered capacity-distance requirements. In contrast we found that the optimal cables for the SDM systems are the ones that can fit just right amount of fibers needed for those systems.

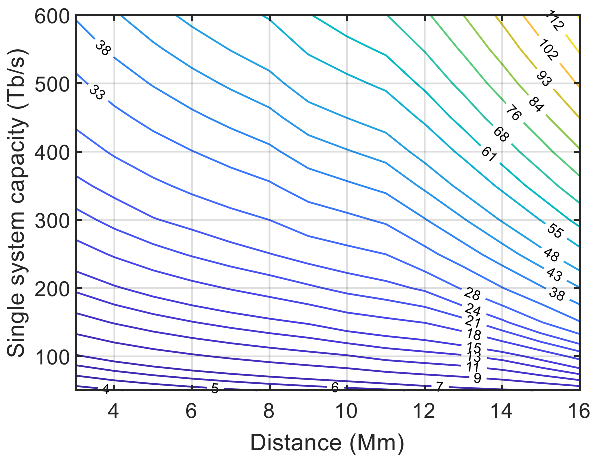

Figure 4. Optimal number of fibers in cable

Figure 4 shows the number of fibers for the cost-optimized SDM system. This result is for 125 μm^2 fiber with attenuation of 0.155 dB/km. As we observed in simulations with various fiber types, the optimal number of fibers does not vary significantly due to fiber effective area or cost per km.

Figure 5 shows the spectral efficiency range supported by each single mode fiber of an SDM system. It demonstrates that transponders may need to operate at quite low efficiencies near 2 b/s/Hz for longer systems to achieve minimum cost.

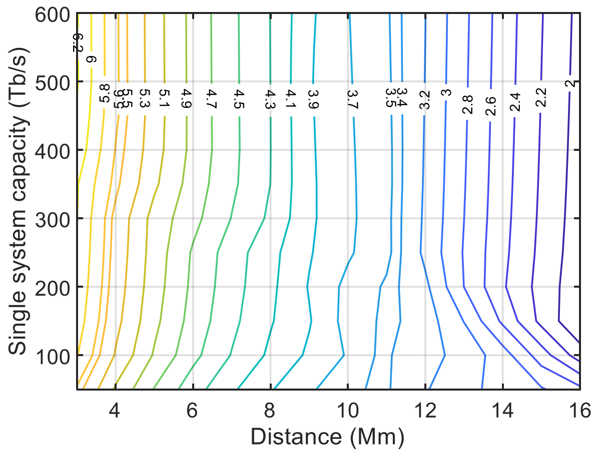

Figure 5: Spectral Efficiency (b/s/Hz) for optimal solutions

We observe repeater spacing to vary between 100 km for short and low capacity systems, down to 75 km for the longest systems. Most of the considered capacity-distance area has repeater spacing around 80 km. For the system shorter than 12,000 km SDM index is around 2, meaning that one pump serving 2 amplifiers is the economically optimal solution for most of the considered capacity/distance area. For the same area the amplifier output power is 1 to 2 dB below the power required to reach nonlinear capacity optimum. As we go longer in system length, the amplifier output power goes down, to 5 dB below nonlinear optimum and the SDM index goes up to 6. Longer distances are truly “SDM area” where the system becomes linear and each pump serves many amplifiers, while the systems shorter than 12,000 km are still close to the nonlinear optimum and thus can moderately benefit (< 1 dB SNR gain) from nonlinear compensation if available without SLTE cost penalty.

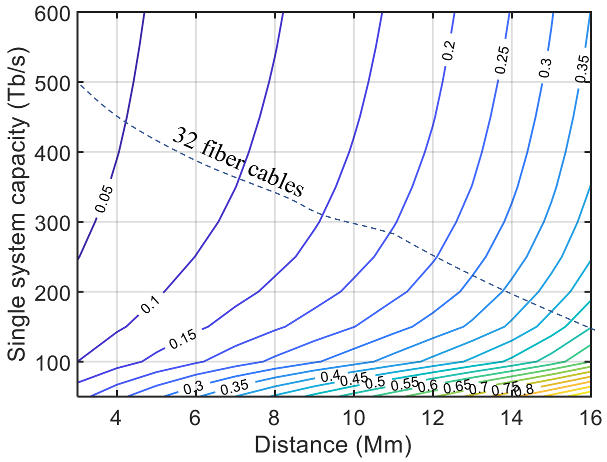

Figure 6: Normalized cost per capacity for system

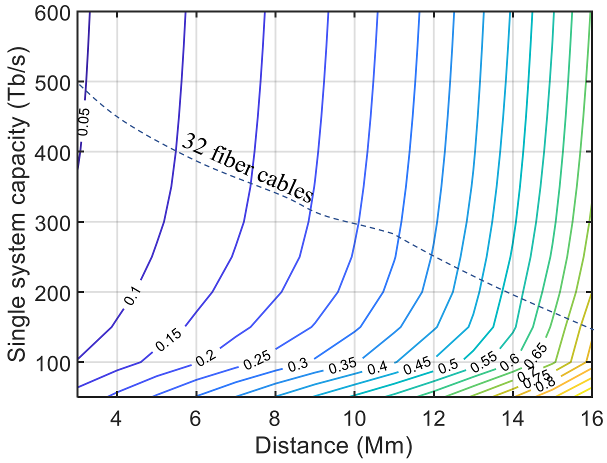

Figure 7: Normalized cost per capacity for wet-plant

Figure 6 is the contour plot for normalized system cost-per-capacity defined by Eq. 1. As a reminder, the system cost is comprised of all costs associated with the system, including terminals, modems, installation costs, permitting, etc. Results for the wet-plant only costs (the equipment cost that goes under water) are shown in Figure 7. One can see that for every distance in Figure 7, there is a knee point, above which the cost per capacity contour lines go vertically. This means that exceeding this "knee point capacity" does not lead to noticeable reduction in cost per bit for the wet-plant. The same knee point is still present in Figure 6 as well, however the knee is not as sharp. Still, for each distance, there is a range of capacity, exceeding which has a diminishing cost-per-capacity return. It is interesting to note that this knee point roughly coincides with 32 fiber cables shown as a dashed line in figures 6 and 7. Therefore, we believe that a 32-fiber based system is a good logical choice for next generation submarine systems using SDM. Our simulations also show that the 32-fiber number is relatively robust with respect to other assumptions about the system, for example effective area of the transmission fiber.

Interestingly, we do not observe capacities for which system cost-per-capacity values stop decreasing with capacity increase. That is, we do not see cost-per-capacity optimum vs capacity. We checked this statement up to 2 Pb/s. Arguably our model is not valid for larger values, because we do not account for some extra costs associated with thicker cables. We attribute the absence of the optimum to the fact that we adjust the cable design to fit more fibers and increase cable conductivity as needed. This contrasts with publication [8] where such an optimum exists, and the cable model is not considered.

So far, we have presented the results extrapolating capabilities of today's technology. It is interesting to speculate what will happen with the technology of the future, with significantly decreased cost per spatial path. On the one hand it should lead to an increase in the number of parallel paths. On the other hand, the larger number of fibers may lead to thicker cables with higher conductivity. This would reduce the required SDM index and the number of spatial paths. A precise balance between cable conductivity and number of spatial paths is needed. It is not clear, for example, if such technologies as multi-core and multimode fibers would have an advantage requiring less space in a cable, because they may still require higher conductivity cables to supply more power to the repeaters in order that all spatial dimensions are amplified; and high conductivity cables may have enough space for SMF fibers anyway. To answer these questions and to find optimal solutions we need similar simulations and optimizations as described here but with different assumptions reflecting capabilities and costs of the future technologies.

5. CONCLUSION

We present our SDM system simulation model and describe the results for cost-per-capacity optimization for future submarine systems. We find 32-fiber solution to be an attractive system target. While further system cost-per-capacity improvement can be achieved for even larger fiber count, this improvement is less dramatic and wet-plant only cost-per-capacity metric does not improve. Further reduction of the cost-per-spatial path is required to maintain the pace of the cost-per-capacity improvement. We demonstrate the importance to include signal droop into modeling, as well as cable design aspects, when considering optimal SDM system designs. We also show the spectral efficiency range expected from transponders and note that nonlinear compensation could provide moderate benefits (<1dB SNR gain) for cost-optimized SDM systems below 12000 km.

6. REFERENCES

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