Optical technologies to disclose the spatial diversity dimension in systems and networks

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Abstract: *The spatial dimension is the key dimension which can enable exponential growth of data capacity in networks. Optical technologies offer a wealth of opportunities to disclose this dimension, notably in optical fiber transport and access networks, in mm-wave radio networks and in optical wireless networks.*

1. Introduction

The exponentially growing needs for communication capacity, fueled amongst others by the booming of internet services and video-based (interactive) services, is putting heavy loads on both wired and wireless networks. Optical fiber has proven to be a vital medium to transport huge traffic streams over long distances, such as in transoceanic links, as well as in metro and access networks. Several dimensions in the signal space have been exploited to increase data transport capacity: the time domain by increasing the speed of the (opto-)electronics, the frequency domain by opening up more radio frequency bands, the wavelength domain by widening the optical spectrum range, and combinations of those such as time/frequency coding. In general, extending these dimensions enables a linear growth of capacity, and the possibilities for this are running into the limits of electronic and optical means. To accommodate exponential growth of a network's capacity, however, yet another approach is required in addition: the spatial dimension, which can be exploited by introducing more and more distinct spatially-separated transport modes in the wired medium, and ever smaller cells in the network architecture. E.g., each time when halving the cell size in a network, the capacity of the network is doubled (while keeping the same capacity per cell).

Optical technologies offer great opportunities to exploit this spatial dimension. In this plenary talk, these opportunities for both the wired and the wireless parts of communication networks will be addressed.

2. Spatial division multiplexing in point-to-point optical links

In today's optical networks typically standard single-mode fiber (SMF) is used, operating in the fundamental LP01 mode which offers a high bandwidth and low losses. A first step to double capacity in the spatial domain is to use the two orthogonal polarization states. But major steps can be taken by means of the higher-order modes which become available at higher V-numbers, so when operating in the few-modes regime of fibers having a somewhat larger core. As a bonus, such larger cores also alleviate the non-linearity issues and hence allow operation at higher optical signal power levels. Already in 2002, we started to investigate how in multimode large-core silica fiber spatial division multiplexing can be used [1]. We partitioned the large volume of modes (e.g. about 146 modes at $\lambda=1.3\mu m$ in a $50\mu m$ core parabolic graded-index multimode fiber, GI-MMF) into subsets of modes, so-called mode groups, and each mode group can act as a separate communication channel. Moreover, the propagation path differences between the modes within a mode group are smaller than those within the total volume of all modes, hence the bandwidth of a mode group is larger than the modal-dispersion limited bandwidth of a graded-index fiber. We showed the feasibility of this MGDM (mode group division multiplexing) concept by demonstrating 3x 10Gbit/s transmission over a short length (20 meters) of $\varnothing185\mu m$ core GI-MMF. The spatial division multiplexing (SDM) technique was introduced by Peter Winzer c.s. at Bell Labs Holmdel, disclosing in a few-moded fiber (FMF) on top of the fundamental LP01 mode the next-higher modes LP11, LP21, LP02, etc., and their degenerates [2]. The European R&D cooperation project MODE-GAP, started in 2010, pursued SDM in hollow-core fiber. In this project, we designed a passive monolithic silicon-on-insulator PIC to multiplex 6 SMF LP01 input ports into a single FMF carrying 6 channels, namely the LP01 in s- and p-polarization, and LP11a and LP11b each in 2 polarizations [3]. With this mode set and a 7-cores fiber, we achieved 255Tbit/s over 1 km [4]. Larger numbers of SDM channels are being obtained with passive fiber-fused photonic lanterns, and with multi-core few-moded fibers aggregate data capacities beyond 10Pbit/s have been achieved.

Spatial division multiplexing in the radio domain can be realized by exploiting the different orbital angular momentum (OAM) modes of a radio wave which each have a distinct rotationally varying phase front. Such OAM modes constitute orthogonal data transport channels multiplexed within the same spatial area. Thus, in a radio point-to-point link the total data capacity can be multiplied without requiring more radio spectrum. The rotational phase profiles for the respective OAM modes needed at the transmit and receive sites can advantageously be created by

optical phase shift techniques [5]. Wavelength-dependent optical phase shifters in combination with radio-over-fiber signal transport enable the seamless coupling of WDM fiber channels into OAM radio channels, and thus can create spectrum-efficient high-capacity radio wireless links cooperating nicely with fiber networks.

3. Dynamically reconfigurable optical fiber access

Partitioning a network in smaller cells may not only increase its overall capacity, it also adds flexibility and enables dynamic network reconfiguration in order to respond to changing local traffic loads. In particular in fiber access networks where individual homes are to be connected the fluctuations in local traffic loads may be substantial. In the well-known power-splitting passive optical network (PON) fiber-to-the-home (FttH) access networks, the access per home typically is arranged by a TDMA (time division multiple access) protocol. Multiple wavelength channels can be used which can be flexibly multi-casted among the homes and where in each wavelength channel multiple homes are served according to a TDMA protocol. Thus, larger traffic fluctuations per home can be accommodated, as individual loads which are going to exceed the available TDMA capacity in a wavelength channel can be re-assigned to another wavelength channel which still has room to accommodate these. As a net result, we showed that this flexible wavelength-time-division multiplexing (WTDM) concept allows higher total network throughputs within an allowable congestion probability limit [6]. Such flexible WTDM concept may be implemented in a λ-broadcast-and-select architecture, which is most suited for access networks where on top of individual services also broadcasting services are to be delivered. We have explored this in a hybrid fiber-coax network architecture [7]. The flexible WTDM architecture may also be implemented in a dynamic λ-routed architecture, where wavelength channels are multi-casted to network cells according to their instantaneous needs. We explored this in a hybrid fiber-wireless network, where a wavelength router in the network splitting node multi-casted towards radio antenna stations for LAN applications [8]. Within a building, a compromise between system complexity (and thus CAPEX costs) and the capability to handle fluctuating traffic loads can be made by choosing the appropriate size of re-allocatable clusters of rooms [OFC2011].

4. Radio-over-fiber pico-cell wireless networks

As stated by Cooper's Law, the introduction of ever smaller radio cells has been of major importance to increase the capacity of radio-based wireless networks. Given a certain area to cover, a smaller cell size implies that more antenna stations are needed, and in order to keep total costs manageable these antenna stations should be as cheap and therefore as simple to install and to operate as possible. Analog radio-over-fiber (ARoF) techniques are attractive in which the complete radio signal, comprehensively modulated on an RF carrier, is modulated on an optical carrier and as such brought tov the antenna station where a simple photodetector plus RF booster amplifier suffice to radiate the radio signal into the cell. Such an ARoF approach is relatively agnostic to the signal modulation format and the RF carrier frequency (within the operational bandwidth of the antenna station, of course), and this offers the additional advantage of easy upgradability to new radio standards.

The ARoF approach is quite attractive for establishing indoor pico-cell wireless network architectures. By employing multiple wavelength channels each transporting one or more ARoF signals and flexibly allocating these channels to the rooms, it offers large flexibility to handle traffic loads which move around among these rooms (as may happen in e.g. schools and business centers). We also showed that the introduction of pico-cells instead of a large single indoor cell reduces the total energy consumption of the whole in-home system [9]. It can lower this consumption even more because the dynamic allocation of capacity to rooms enables to offer capacity-on-demand to every room, thus avoiding to offer static capacity to places where it is not needed [10].

5. Radio beam steering

As a next level to the introduction of radio pico-cells, a further increase of capacity density can be achieved by introducing relatively narrow radio beams which each cover only a part of a room. Such beams need mm-wave radio frequencies (e.g. in the 57-64GHz band) to achieve a large operational bandwidth and to enable compact directive antenna designs. Phased array antenna structures consisting of many antenna elements are well-known for their ability to steer a beam into a direction which is specified by the RF signal's phase difference between adjacent antenna elements. The more antenna elements are used, the higher the antenna's directivity and thus its gain is. Typically, the phase difference is set by adjustable RF phase shifters, one per antenna element, which for such mm-wave frequencies is challenging. The multitude of mm-wave electronics needed also makes it a power-hungry solution. Alternatively, in conjunction with ARoF techniques as mentioned before, adjustable optical delay lines may be used to set these phase differences. We explored wavelength-selectable time delay solutions which are based on an arrayed waveguide grating router (AWGR) with feedback loops of different lengths. Adjusting the wavelength of the ARoF signal implies that a specific feedback loop is selected, and thus a specific discrete delay time. Such a λ-tunable true-time-delay (TTD) cell is attractive to be used as a key element in a 2-dimensional matrix architecture.

This matrix can achieve mm-wave beam steering in 2-dimensions by only varying the wavelength of the ARoF signal, if the free spectral ranges (FSR) of the AWGR stages in the rows and columns respectively are designed such that a complete row-by-row scanning is achieved when tuning the wavelength over the whole available wavelength range. Applied in a phased array antenna architecture, the TTD technology implies that the beam steering is determined by the actual time delay and not by the mm-wave phase shift, which makes the beam steering frequency-independent and thus creates a wide operational RF bandwidth without the footprint-enlarging beam squint typically associated with phase-tuned beam steering. As the beam direction is determined by the wavelength tuning of the ARoF signal, this steering can be controlled remotely by e.g. using a λ-tunable laser diode in the ARoF optical transmitter at a centralized site. Thus, no local comprehensive control circuitry at the antenna site is needed, which eases installation and maintenance, as well as network management and control. We have implemented our λ-tunable TTD beam steering concept in a compact silicon-on-insulator PIC for a simple 2x2 phased array and showed its feasibility by transmission of 8Gbit/s QAM-16 signals at 38GHz carrier frequency where we obtained ±37.6° beam steering at 26cm reach [11].

6. Optical wireless

Maximizing the data capacity which can be provided to a given area can be done by minimizing the diameter of a beam and maximizing the packing density of the beams. Optical lens systems can create (nearly) collimated narrow optical beams. To achieve the equivalent gain of a well-designed lens system, a mm-wave phased-array antenna needs to have a very large number of elements and very comprehensive control; it thus will consume quite some power, whereas the optical lens system is fully passive. Narrow infrared optical beams are attractive for energy-efficient ultra-high capacity data transport: each beam can address an individual user device, and by being directed on-demand to a device where and whenever needed, no energy is wasted. The high directivity assures privacy (only the device being addressed is able to receive the data), and maximizes the link power budget and hence the achievable capacity. A narrow infrared optical beam is virtually equivalent to an optical fiber, but without being a wire; its capacity can even surpass that of a fiber, as the beam does not suffer from waveguide dispersion. Using a wavelength in the eye-safe regime of λ>1.4μm, the beam's power may be up to 10mW. Setting up connections with such narrow beams also requires careful beam steering, and accurate localization of the users' devices.

Beam steering with active modules (MEMS mirrors, spatial light modulators, …) has been successfully investigated. We explored passive diffractive modules with which we could achieve the 2D beam steering by just tuning the wavelength of the beam [12]. In particular, we explored the use of a crossed grating pair and of a high-port count wavelength demultiplexer with its optical outputs carefully arranged near the focal plane of a wide-aperture lens. The beam's diameter at one hand has to be relatively large in order to ease localization of the user and the alignment of his device, but at the other hand be narrow in order to maximize the optical power captured by his optical receiver. We built a laboratory demonstrator wherein beams of about ∅10cm are used, and demonstrated successful transmission of high-definition video movies embedded in two 10GbE streams carried by two independent beams in the 1.5μm window [12]. For device localization, two techniques are explored: by camera observation, or by retroreflection using an array of miniature corner cubes. The first technique requires active tags at the device and calibration of the camera read-outs of the device's location to wavelength settings for the beam steering; it allows instantaneous tracking of the devices. The second one does not require active power-consuming functions at the device and by scanning the area with a beam this technique is auto-calibrating the device location to the wavelength setting; the scanning process takes some more time for tracking the devices [13].

7. Concluding remarks

The spatial dimension is of vital importance to accommodate the explosively growing data transport needs in communication networks. Optical techniques offer powerful opportunities for exploiting this dimension in transport, access and indoor networks, not only increasing their capacity, but also improving their flexibility and energy efficiency.

8. References

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