Thailand, has lost some of its capacity for producing fibre-optic connectors.

Companies that contract with Fabrinet mostly sell to large telecommunications equipment vendors such as Alcatel-Lucent, Ciena and Cisco, who will only see a small impact from these events. There will be even less effect on telecommunications service providers. "The companies close to the bottom of the food chain are the ones who get hurt," explains Innis. "The impact on the AT&Ts of the world will be minimal."

Perhaps a bigger problem will be the drop in demand seen in recent months, coupled with the difficulty in projecting future sales, explains Innis. He projects that continuing financial problems in the Euro zone are likely to shrink the market by 7–9%. "Everyone is spending very cautiously because they're not really sure how the financial markets are going to evolve."

Innis believes that the flooding has simply added another level of unwanted stress to the supply chain. However, component manufacturers are expected to bounce back very quickly, just as electronics manufacturers did after the earthquake and tsunami in Japan earlier in 2011. "The industry is demonstrating its vitality and its resilience as it goes through these different problems," says Innis. ❒

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VIEW FROM... OSA FRONTIERS IN OPTICS 2011

How many bits can a photon carry?

Quantum physics offers a way to enhance the amount of information a photon can carry, with potential applications in optical communication, lithography, metrology and imaging.

David Pile

Light is a popular medium for transmitting data, but how many bits of information can a single photon carry? It turns out that the answer is many, thanks to quantum entanglement and the photon's many degrees of freedom, including frequency, time of arrival, and spin. The most pressing question, however, is whether these properties can be practically exploited to enhance applications such as imaging, communications and lithography. Furthermore, would such improvements be marginal, or span many orders of magnitude? These questions were among those explored at the 95th annual meeting of the Optical Society of America, Frontiers in Optics 2011. The meeting, co-located with Laser Science XXVII (the annual meeting of the American Physical Society's Division of Laser Science), took place in San Jose, California, USA, on 16–20 October 2011.

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The conference explored a range of ways to encode more bits onto fewer photons, while also tackling questions regarding the upper limits of multibit-per-photon technology.

Carrying more information using fewer photons would benefit a wide range of applications. Two obvious examples are for improving the bandwidth of communications systems, and for imaging objects at low light levels. One can even envisage defence applications such as targeting in low-light conditions and low-signal-power communication for covert operations.

The series of sessions at the conference on these topics, entitled "Information in a photon", carries the same name as a DARPA (Defense Advanced Research Projects Program) programme on the subject (www.darpa.mil/Our_Work/DSO/Programs/Information_in_a_Photon.aspx).

"One of the aims is to transmit ten bits of information per photon. A wide range of different technologies are being pursued for encoding at the single-photon level, including orbital angular momentum, frequency and temporal modes," explained Geoff Pryde from Griffith University in Brisbane, Australia, who gave a talk on the related topic of quantum metrology. "An interesting development is the translation of code division multiple-access schemes from radiofrequency and microwave technologies such as cell phones to the photonic regime," explained Pryde. "Here, different states overlap in frequency and temporal modes, but with orthogonal wavefunctions, thus allowing them to be distinguished. Significant research efforts are underway to design optimal receiver schemes for multiplexing and demultiplexing highly encoded photonic signals."

Franco Wong (Massachusetts Institute of Technology, USA), who gave a talk on an efficient periodically poled potassium titanyl phosphate waveguide source of time–energy-entangled photons, told *Nature Photonics* that although multibit-per-photon approaches may indeed yield gains, several important issues must be addressed.

"We are only beginning to look at some of these issues and perform initial experiments to find out what the ultimate limits are, what kind of complexity is involved in the implementation, and what the technical limitations are, including in terms of efficient detectors, path losses and noise," Wong explained. "One also has to consider the issue of security and the protocol most suitable for the chosen degrees of freedom.

The source demonstrated by Wong and co-workers is capable of producing nearly 100 million photon pairs per second with 10 mW of pump power. Over a time frame of 10 ns, the arrival times of a photon pair — one at location A and the other at location B — are uncertain but tightly correlated in time. Arrival time is another degree of freedom that can be used to encode information. In pulse-position modulation coding, a scheme typically employed in classical communication, the arrival time of a photon can represent n bits of information if there are 2^n time bins within the 10 ns time frame. The researchers have demonstrated time–energy entanglement in six 400-ps-wide time bins over a time frame of 10 ns, limited mainly by the 25% duty cycle of the InGaAs single-photon counters (gated every 1.6 ns).

This demonstration represents 2.6 temporal bits per photon in a 10 ns frame, which Wong claims can be extended to 4.6 bits per photon if the detector could be operated continuously. The group aims not only to increase the number of temporal bits by decreasing the time bin width to 40 ps, but also to add spectral bits by introducing standard dense wavelength-division multiplexing technology. The hope is to reach over ten bits of information per photon for use in high-data-rate quantum key distribution.

Saikat Guha from Raytheon BBN Technologies in the USA agrees that attaining higher bit-per-photon levels may be just around the corner, particularly for systems such as deep-space communication links. He points out that high-photon-efficiency communication (many bits per photon) can be attained only when the photon flux — the received average photon number per modulated pulse — is very small. This makes it appropriate for deep-space communication, such as for links between a geostationary satellite and Mars. Deep-space communication is inherently photon-starved because the received photon flux is limited by the transmitter's power, range, and pointing and tracking accuracy.

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Frontiers in Optics 2011 involved five days of cutting-edge research presentations, powerful networking opportunities and engaging educational programmes.

"In low-photon-flux links operating at say, around one received photon per 5 ns pulse interval, a higher photon efficiency would immediately translate to an increased data rate," Guha explained. "The best photon efficiency demonstrated over a deep-space link is around two bits per photon. Attaining ten bits per photon on a similar link seems reasonable in the near future."

Guha told *Nature Photonics* that one of the team's goals is to design a 1-km-range terrestrial free-space communication system with a photon efficiency of ten bits per photon, a spectral efficiency of 5 bit s^{-1} Hz^{-1} and a reliable communication data rate of 1 Gbit s^{-1}. Guha also says that this may be achievable with only around 13 pW of received power.

Low-power transmission has significant potential for use in private communication, as the probability of small numbers of photons being detected by a third party is inherently low. Data could even be transmitted at very low power levels on purpose — a technique that could be particularly important for defence applications, where signals are often sent through free space.

The fields of imaging and metrology (including lithography) could also benefit from this technology. Guha emphasized that low light levels would be particularly advantageous to biological imaging applications, where low photon numbers naturally imply a minimally invasive procedure.

Another potential application is using low light levels to read coded information stored on an optical disk or bar code, whose pixels encode information by modulating the amplitude and/or phase of the probe light. Guha explained that a single photon prepared appropriately in a spatially entangled quantum state can theoretically be used to read any amount of information.

"We have shown that the quantum states of light fundamentally outperform classical light probes," said Guha. "We found an explicit spatially entangled 'W-state' transmitter — a single-photon in a coherent superposition of multiple orthogonal spatial modes — that is capable of reading a binary-phase-encoded target using a Hadamard code and a fairly simple structured receiver at a rate of 5 bits per photon (error rate of <0.001) with only 32 memory pixels. The absolute minimum for a classical transmitter with optimal code and a yet-unknown receiver is 4,800 pixels."

There seems to be significant room for improving photon efficiency in low-light imaging, quantum communications and deep-space communication. However, it is very difficult to predict how far this potential reaches.

"A further extension is to quantum imaging, where it will be interesting to see if entanglement can provide real advantages by improving signal-to-noise ratios or imaging resolutions," Pryde explained. "Although such a scheme is theoretically possible, experimental realization is challenging because real-world environmental noise quickly degrades entanglement." ❐

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