But irreversible logic isn't the only way to compute. An experimental form of computing called reversible logic doesn't necessitate destroying information. So, in principle, it could dodge Landauer's limit, its proponents say.

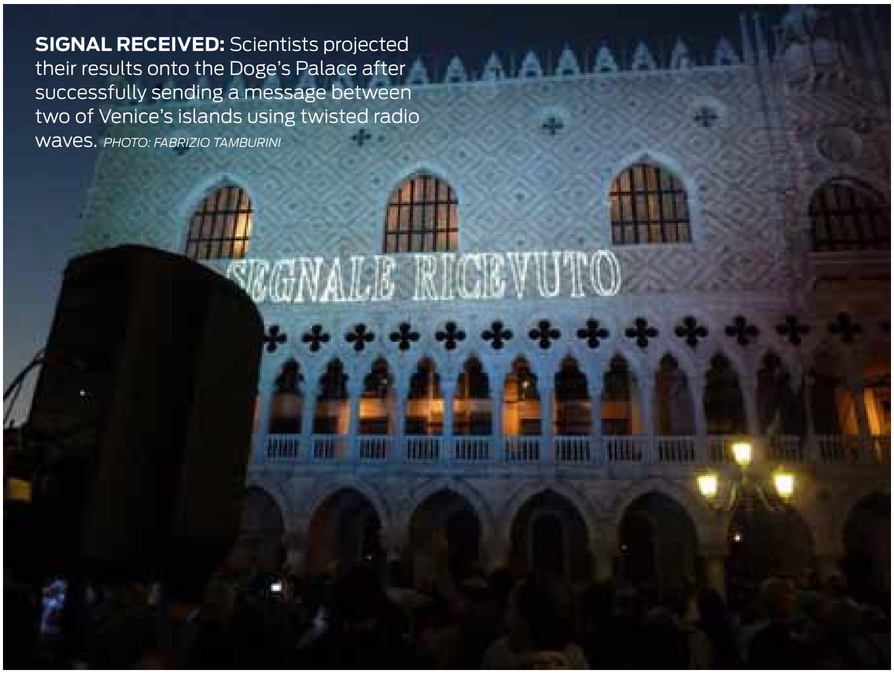
According to Gregory L. Snider, professor of electrical engineering at the University of Notre Dame, in Indiana, reversible logic does just that. In results to be published in the *Japanese Journal of Applied Physics*, he and his colleagues report an electronic reversible logic system that gives off less heat than Landauer's limit. "There is no limit if you're doing it reversibly," says Snider.

The need to get past this limit isn't urgent today, but extrapolating Moore's Law to that limit leads to some absurd ends. A chip built about a decade from now near the limit would throw off more energy per square centimeter than the surface of the sun, Snider estimates.

But others are skeptical of reversible computing's chances. Ralph K. Cavin, chief scientist at Semiconductor Research Corp., in Research Triangle Park, N.C., points out that electrons, unlike microscopic glass beads, can randomly tunnel through an energy barrier by virtue of their quantum nature. Any electronic computing scheme looking to dodge the Landauer limit would need to correct for that, and that correction would give off heat. In fact his colleagues christened the imaginary monster doing the job "Cavin's Demon."

Cavin acknowledges that low-power computing is critical, but he doubts the Landauer limit can be surpassed. "It's a bit like perpetual motion: dreamed of… but not doable." —Samuel K. Moore

A version of this article appeared online in March.



SIGNAL RECEIVED: Scientists projected their results onto the Doge's Palace after successfully sending a message between two of Venice's islands using twisted radio waves. PHOTO: FABRIZIO TAMBURINI

A New Twist on Radio Waves

Using the angular momentum of light could make one radio channel into two, or three, or more. But many wireless experts are skeptical

By now, you'd expect that communications engineers would have explored every trick in their century-old effort to cram more data into a limited number of frequencies.

But researchers in Italy and Sweden have shown that there is still uncharted territory. A little-explored quantum property, they claim, has the potential to boost the number of channels available in a single-frequency microwave link, perhaps as much as elevenfold.

In early March the researchers simultaneously transmitted two radio beams at exactly the same frequency between two of Venice's islands, a distance of 442 meters. The signals were received and decoded as clearly as if they'd been sent at two different frequencies. Ordinarily, coding schemes require either different frequencies to distinguish the signals or the division of a channel into time slots.

The new trick hinges on using a quantum state of photons called orbital angular momentum. A photon can carry angular momentum just as a rotating body does and can even transfer the momentum to small particles, causing them to rotate. The orbital angular momentum of photons has been intensively explored in the optical region of the electromagnetic spectrum. But its study in the radio-frequency region is quite new.

In theory, a photon can occupy an infinite number of these quantum states, each associated with an integer value. These quantum states impart the radio beam with a distribution of phases as it travels through space that gives the beam the shape of fusilli pasta (a helix).

The researchers started with two off-the-shelf transmitters and receivers designed to operate at the Wi-Fi frequency of 2.414 gigahertz. "We chose this fre-

update

SLIGHT TWIST: Bending a dish antenna let researchers project twisted radio waves.
PHOTO: FABRIZIO TAMBURINI

quency because equipment that can easily be controlled is available," says Fabrizio Tamburini, an astrophysicist at the University of Padova, in Italy. The setup also included two Yagi-Uda antennas (similar to old television aerials) for reception and a radio dish and Yagi-Uda antenna for transmission, all commercial models. But the team modified the dish antenna by bending it into a somewhat helical shape.

The shape of the dish was important, because when an ordinary wave of radiation from the antenna horn struck it, what reflected off was a wave whose phase was shifted into the shape of a continuous helix, corresponding to an orbital angular momentum of 1. At the same time, a beam of exactly the same frequency was emitted with a Yagi-Uda antenna, which imparted no phase twist, corresponding to an orbital angular momentum of 0.

At the receiver, the team could easily separate the twisted radiation from the nontwisted beam by measuring the phase.

Tamburini stresses that the experiment was just a proof of principle and that real-world systems for data transmission will use phased-array antennas for transmission and reception instead of bent dishes. These consist of arrays of small antennas, each fed with a signal at a shifted phase to create the helical wave.

Tamburini and his colleagues plan to perform experiments with more transmission channels and to develop smart phased-array antennas that can generate radio waves with several orbital angular momentum states simultaneously. Tamburini says that satellite companies are interested in the technology and that he and his colleagues plan to start a spin-off company in collaboration with the university.

Convincing communication companies that twisted radio waves can add capacity where there was none before will require the simultaneous demonstration of three or more channels at the same frequency, each having different angular momentum, argues Michael Steer, an RF and microwave expert at North Carolina State University. "That would have been convincing; now the [researchers] are really asking us to trust them."

Indeed, some radio communication specialists are skeptical, saying that the technique will add no capacity. Ove Edfors and Anders J. Johansson, both at Lund University in Sweden, argued in the February 2012 issue of *IEEE Transactions on Antennas and Propagation* that at its heart, radio transmission using orbital angular momentum is no different from the multiple-input multiple-output (MIMO) communication technology in use today. MIMO, which involves transmitting and receiving on several antennas, increases data throughput and range without increasing power or using more bandwidth. Though the Lund group submitted their paper before the demonstration in Venice, Edfors says, "I still argue that this is traditional MIMO, but with a more esoteric antenna."

Stephano Maci, an IEEE Fellow and antenna expert at the University of Siena, agrees. "I have some doubt about the practical feasibility of actual systems based on radio vorticity. One should compare this system to a MIMO system," he says.

—Alexander Hellemans