Communication in a Disordered World

Rather than decreasing efficiency, scattering can actually increase the information transfer rate for cell phones and other wireless microwave communication devices. Mesoscopic physics helps explain how.

Steven H. Simon, Aris L. Moustakas, Marin Stoytchev, and Hugo Safar

Over the past decade, we have seen a revolution in the ways we communicate. The Internet has created the demand for extremely high information transfer rates, while cell phones and other mobile wireless devices have fueled the desire for ubiquitous connectivity for a dense population of users. The near future promises the merging of these two worlds: wireless high-bit-rate devices.

Perhaps the most fundamental hurdle on the road toward this dream is the relatively low bit rate that current wireless systems can provide.[1] The limit for the amount of information—known as the information capacity I—that can be sent between a single transmitter and a single receiver is given by Claude Shannon's famous formula:[2,3]

$$I = \log_2\left(1+\frac{S}{N}\right) \quad \text{bits s}^{-1}\,\text{Hz}^{-1}, \tag{1}$$

where S is the received signal power, N is the noise power, and information is measured in bits per second per hertz of bandwidth available for transmission. (For an explanation of this formula, see the box on page 40.) With the maximum power limited and the frequency spectrum overcrowded (already making a few megahertz of bandwidth worth billions of dollars), Shannon's expression does not seem to leave much room for increasing the information capacity.

Over the past five years, multiantenna arrays have increasingly been suggested as a way to stretch Shannon's limit.[1] The simplest multiantenna array, the "steered beam" or "phased" array, consists of several individual antennas that each transmit the same signal but with a different phase shift. The phase shifts are arranged so that the different signals interfere constructively in one direction and destructively in all other directions. This idea, which dates back to World War II, allows the output power to be aimed in a particular direction. Furthermore, one can change this direction electronically just by changing the phase shifts between the antennas.

At the receiver end, the story is similar. The signals received from each of the individual antennas can be summed with different relative phase shifts. With appropriately chosen phase shifts, the summed signals can be made to interfere constructively if the electromagnetic wave is incident on the receiving array from a given angle and to interfere destructively if the wave is incident from any other angle. In this way the receiver can be made to "look" in an arbitrary direction.

In many real environments (say, in buildings or in cities), microwaves with wavelengths of roughly 10–30 cm (typical for modern wireless devices) are readily scattered by surrounding objects—walls, desks, cars, and so on. In the presence of such scatterers, there are a multitude of paths from the transmitter to the receiver. One might expect that a beam-steering approach would not work in this situation. However, by using what are known as intelligent-antenna techniques, one can still obtain an increase in received power.[1] These techniques exploit the time-reversal symmetry of Maxwell's equations. Each of the antennas in an array (at a base station, for example) measures the relative phase and amplitude of the signal arriving from a particular source (such as a cell phone), then transmits with the same relative amplitude but with the opposite phase. This approach guarantees that all of the transmitted signals interfere constructively at the receiver. These intelligent-antenna techniques can even be used when there is a wide range of time delays resulting from the differing path lengths from transmitter to receiver. In that case, however, more computational processing power may be required to calculate the proper signal to send. Similar time-reversal tricks have been used with acoustic waves for imaging and other applications (see the article by Mathias Fink in Physics Today, March 1997, page 34).

Beam steering and intelligent antenna techniques increase the signal directed toward an intended receiver and reduce the reception of stray signals intended for other targets, which appear at the receiver as noise. Overall, the relative gain in power obtained from using an array with M antennas is roughly a factor of M (for fixed total transmitted power). Although increasing the signal is certainly desirable, it only increases the information logarithmically (equation 1). Thus, trying to increase the bit rate by increasing the signal-to-noise ratio is a game of rapidly decreasing returns.

In 1995, Gerry Foschini at Bell Labs realized that the key to beating the log is to exploit scattering.[4] The multitude of paths in a scattering environment—while appearing to only complicate matters—turns out to allow for a much larger information transfer! Very roughly, a different signal (a different bitstream) can be sent over each distinct path between the transmitting and receiving arrays, thus increasing the information transfer rate many times. Even more important, Foschini came up with

Steve Simon *is director of biological computation and theoretical physics at Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey.* **Aris Moustakas** *is a member of the technical staff at Lucent Technologies' Advanced Wireless Technology Laboratory.* **Marin Stoytchev** *and* **Hugo Safar** *are members of the technical staff at Agere Systems' Electronic Device Research Laboratory in Murray Hill, New Jersey.*

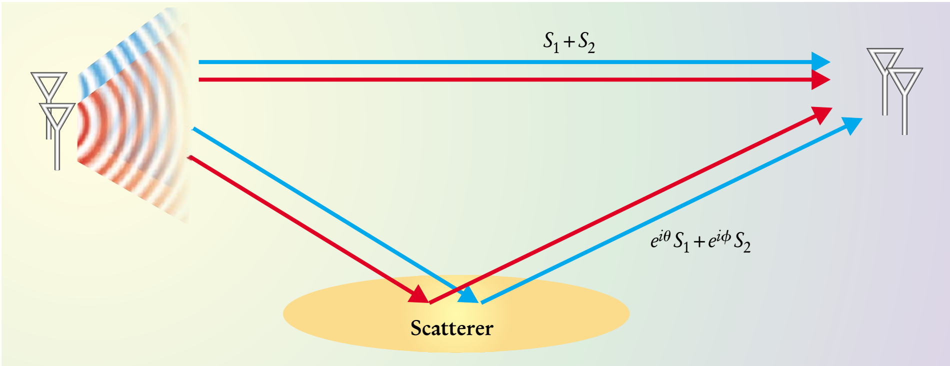

FIGURE 1. SCATTERING ENHANCES INFORMATION transfer rates. In the absence of scattering, both receiving antennas see the same linear combination of the two transmitted signals. Thus it is impossible to distinguish the separate transmitted signals. In the presence of the scatterer, a second linear combination is also received. If the antennas are at slightly different spatial positions, an inverting linear transformation can be used to determine the two different transmitted signals. With two independent signals communicated simultaneously, the information transfer rate is roughly doubled.

a coding and decoding algorithm, now known as BLAST, that obtains these higher information-transfer rates even when the details of the scattering environment are not known. The general idea of sending multiple signals between multiantenna arrays is known as MIMO (Multiple-Input Multiple-Output). Since BLAST was made public in 1996, practically every major telecommunications company has been vigorously pursuing MIMO technology. Devices using MIMO will soon hit the market, starting with antenna systems in indoor wireless local area networks (LANs).

It is increasingly clear that multiantenna technology is going to play an essential role in the wireless communication of the future. Here we present the important physics associated with these new technologies.

The MIMO approach

To increase the information rate, we consider sending M_T different bitstreams, one from each of M_T transmitting antennas. If the bitstreams can be decoded at the receiver array, the information transfer rate can become roughly M_T times as large as that for single-antenna transmission (compare equation 1):

$$I \sim M_T \log_2\left(1+\frac{S\,M_R/M_T}{N}\right) \text{bits s}^{-1}\,\text{Hz}^{-1}. \qquad (2)$$

Note that in order to decode the M_T separate transmitted signals, the number of receivers, M_R, must be at least as many as the number of transmitters, M_T. The above expression assumes that the total transmitted power is kept constant regardless of the number of antennas M_T, so that each of the M_T bitstreams is transmitted with power S/M_T. (The intelligent-antenna technique can enhance the received power of each bitstream by a factor of M_R, yielding an effective signal strength of $S\,M_R/M_T$.) Sending M_T different bitstreams can be quite advantageous, since it gives a factor of M_T outside the log, as compared to beam-steering approaches that only increase the information transfer rate logarithmically.

Unfortunately, this promising approach only works if the M_T original signals can be unscrambled from the M_R received signals. One case in which it dramatically fails is when the propagating microwaves do not scatter off any obstacles—the so-called line-of-sight case. The problem here is that if the transmitter array is far from the receiving array (the meaning of the word "far" will be made clear below), all M_R antennas in the receiving array receive essentially the same combination of the M_T different transmitted signals (up to a global phase shift). It is then impossible to distinguish the M_T individual transmitted signals. Thus, beam steering remains the best approach in the line-of-sight case.

This situation can be understood by simple optics. In order for the receiver to "see" that distinct signals are being transmitted from the distinct transmitting antennas, it must be able to resolve a geometric angle of less than $\alpha = L_T/d$, where L_T is the size of the transmitting array and d is the distance between the transmitting and receiving arrays. However, if we think of the receiver as a lens whose aperture is its size L_R, its diffraction-limited angular resolution is $\alpha = \lambda/L_R$, where λ is the wavelength. Thus, if $\lambda/L_R \gg L_T/d$, which is almost always true for cell-phone systems, it is impossible for the receiver to resolve the individual transmitted signals.

Why scattering helps

The presence of scatterers in the environment effectively increases the aperture of the lens that looks at the transmitting array. In other words, the scatterers act as a large complex lens that allows the receiving array to distinguish the several different signals from a relatively small transmitter array. It is critical that, in the presence of scattering, the receiver gets power from a wide range of directions, so that the finite angular resolution of the receiver does not create a limitation.

As a simple example, imagine two transmitting and two receiving antennas, and consider the case, shown in figure 1, where there are two distinct paths from the transmitter to the receiver array: one that is along the line of sight and one that bounces off a scatterer. Generically, the outputs of the two receiving antennas are two different linear combinations of the signals arriving from the two directions. Similarly, the signals from the two directions are two different linear combinations of the inputs to the two transmitting antennas. Thus the outputs are independent linear combinations of the inputs, so the inputs can be deduced from the outputs. Therefore, if two different bitstreams are sent by the transmitting antennas, the receiver will be able to unscramble them. As discussed above, being able to receive two distinguishable bitstreams essentially doubles the transferred information capacity. More generally, if there are M distinct paths from the transmitting to the receiving array, and there are at least M transmitters and M receivers, then the capacity may be increased M times. (The maximum number of fully independent paths that can exist in a scattering environment turns out to be related to the length of time the radiation remains confined in that environment before escaping or being absorbed.[5])

Another way to understand this increase in capacity is to think in terms of phased-array techniques. With appropriately phased inputs to the transmitting antennas,

Information Theory for Physicists

In 1948, when Claude Shannon mathematically analyzed the question of how much information can be conveyed through a noisy communication channel, he uncovered a close analogy between this information and the notion of entropy. The analogy is roughly as follows:

Imagine a transmitter sends us a signal, which is some real number amplitude A that we receive with some noise or uncertainty δA. The transmitter would like to send us a message. We might agree in advance to use the code at left, with A_{max} the maximum value of the signal A. With this code, the transmitter can send 2 bits, or 4 different symbols. This code works perfectly well provided that the noise (or uncertainty) δA is less than roughly $A_{max}/4$. If the uncertainty is greater than this amount, then we won't be able to tell which symbol is intended and the code fails. Roughly, the total number of different symbols one can successfully send is given generally by

Received Signal	Translation
$A = {}^1\!/_4\, A_{max}$	00
$A = {}^2\!/_4\, A_{max}$	01
$A = {}^3\!/_4\, A_{max}$	10
$A = {}^4\!/_4\, A_{max}$	11

$$A_{max}/\delta A \sim \text{“Signal”/“Noise”}.$$

The analogy to statistical mechanics is

Number of Distinguishable Symbols ⇔ *Number of States of the System.*

To draw the analogy further, the number of bits that can be sent is analogous to the entropy:

$$\textit{Bits} = \log_2(\textit{Number of Symbols}) \Leftrightarrow \textit{Entropy} = \log(\textit{Number of States}).$$

Shannon put these statements on firmer mathematical footing by proving the following theorem:[2]

> If a receiver receives complex amplitudes chosen from a Gaussian distribution of variance S and complex noise from a Gaussian distribution of variance N, then the maximum error-free information that can be decoded by this receiver per received amplitude is
>
> $$\textit{Bits of Information} = \log_2[(S + N)/N].$$

This expression contains $(S + N)/N$ rather than S/N because the information should vanish when $S = 0$. If we are allotted a frequency bandwidth B to transmit our signal, then in a time T we can send TB different amplitudes. Equation 1 in the main text then follows, giving the information capacity measured in bits per second per hertz of bandwidth.

One might be concerned that, in a scattering environment, signals may arrive with different time delays (that is, there may be multiple echoes), leading to confusion—and hence lower capacity—at the receiver. This, however, is not necessarily true. The existence of distinguishable echoes can only occur when the speed of changing (modulating) the signal is faster than the echo delays—that is, when the delay time is greater than $1/B$. Thus, if one transmits with a very narrow bandwidth, the communication is immune to these echoes. To take advantage of a wider available bandwidth, one must send different signals on each of many narrow frequency bands.

In the case where there are several transmitters and several receivers, Shannon's formula is generalized to equation 4 of the main text. This expression can be derived quite analogously to the above argument. The question to be asked is always "How many distinguishable signals can be sent from transmitter array to receiver array?" For two receivers, one might consider a code that looks like the one at right. This code would allow us to send 16 symbols or 4 bits, provided again that the noise is less than $A_{max}/4$. Thus, with fixed noise and fixed maximum signal amplitude, one can send roughly twice as many bits from two pairs of transmitting and receiving antennas as with one transmitting and one receiving antenna.

Receiver 1	Receiver 2	Translation
$A_1 = {}^1\!/_4\, A_{max}$	$A_2 = {}^1\!/_4\, A_{max}$	0000
$A_1 = {}^1\!/_4\, A_{max}$	$A_2 = {}^2\!/_4\, A_{max}$	0001
$A_1 = {}^1\!/_4\, A_{max}$	$A_2 = {}^3\!/_4\, A_{max}$	0010
$A_1 = {}^1\!/_4\, A_{max}$	$A_2 = {}^4\!/_4\, A_{max}$	0011
$A_1 = {}^2\!/_4\, A_{max}$	$A_2 = {}^1\!/_4\, A_{max}$	0100
	⋮	
$A_1 = {}^4\!/_4\, A_{max}$	$A_2 = {}^4\!/_4\, A_{max}$	1111

the transmitter can beamsteer one bitstream in one direction (along the line-of-sight path), or beamsteer another bitstream in a different direction (toward the scatterer). By summing the inputs for these two cases (by the superposition principle), the transmitter will simultaneously send one bitstream along one direction and the other bitstream in the other direction. Similarly, two different combinations of the received outputs with appropriate phases will give the incoming signals from the two different directions. Thus each of the two bitstreams can literally be sent over each of the two different paths and be independently received.

Multiantenna information theory

To the information theorist, communication is reduced to a mathematical problem. For M_T different transmitters $i = 1 \ldots M_T$ with inputs T_i, and M_R different receivers $j = 1 \ldots M_R$, we can write the received signal (the output) R_j at the jth receiver as

$$R_j = \sum_i G_{ji} T_i + N_j \,, \qquad (3)$$

where N_j is the noise at the jth receiver, and G_{ji} is one element of the so-called propagation matrix or Green's function. G_{ji} tells how much of the output signal from receiver j comes from transmitter i (along with the appropriate phase). It can be shown (under certain conditions) that, given a propagation matrix G, the maximum information transfer rate is given by[3,4]

$$\begin{aligned} I &= \operatorname{Tr} \log_2(\mathbf{1} + G^\dagger G/N) \\ &= \log_2 \det(\mathbf{1} + G^\dagger G/N) \text{ bits s}^{-1}\text{ Hz}^{-1}, \end{aligned} \qquad (4)$$

with N the noise power, $\mathbf{1}$ the unit matrix, Tr the trace, and det the determinant. Here, $G^\dagger G$ is the matrix equivalent of the signal power S in the single-antenna case (equation 1).

To a physicist, the more interesting part of the problem is the nature of the physical propagation—which in turn determines the information capacity. The challenge then becomes understanding the properties of the propagation matrix G in a complex scattering environment.

With "sufficient" scattering, one hopes that all of the receiving antennas get linearly independent combinations of the transmitted signals, so that it is, in principle, possible to deduce the values of T_i from equation 3 (either by inverting the matrix G or performing a "pseudoinverse" if G is not invertible[6]). If the received signals are indeed linearly independent, the information capacity should be roughly given by equation 2. (The prefactor of M_T in equation 2 comes from the M_T different terms in the trace of equation 4.) However, the condition of linear independence is not always met; its satisfaction depends on both the environment and the antennas.

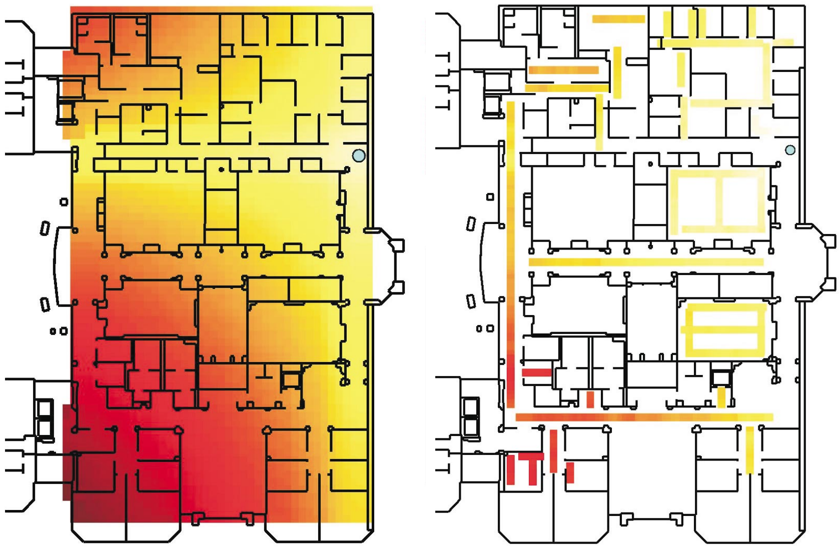

FIGURE 2. DIFFUSIVE MODEL of microwave propagation within a building (left), compared to experimental measurements (right). The transmitter is shown as the blue dot, and the color at a given point represents the log of the received power at that point (yellow is high power, dark red is low power). In the experiments, power was only measured along the colored lines. The results of the diffusive modeling (courtesy of Denis Ullmo and Harold Baranger; see also ref. 9) make very accurate predictions for the amount of power that is received at a given point. The experimental data (courtesy of Reinaldo Valenzuela and Orlando Landron; see also ref. 13) were taken for a study of how to optimize the deployment of base stations for wireless local area networks.

For example, the assumption fails if two receiving antennas are placed right on top of each other. In this case, the two antennas receive precisely the same electromagnetic field, and one of them becomes redundant. (Mathematically, they are receiving linearly dependent signals—we would say that G is not of full rank, or is not invertible.) It is then impossible to determine the individual transmitted signals. Another situation in which G is not of full rank is the line-of-sight case discussed above.

More generally, the receiving antennas may receive correlated (that is, similar) signals, so that although G may be invertible, the inversion procedure is very sensitive to noise. In this case, the information transfer rate is lower than if the antennas were completely independent, but higher than if the antennas were receiving precisely the same signal. It is thus essential to determine how correlated the received signals are for any given antenna array in any particular environment. This determination requires properly understanding microwave propagation in a scattering environment.

Application of mesoscopia

Although at some level all radio propagation reduces to Maxwell's equations, the complexity of real environments makes a complete solution impossible, even numerically, for all but the simplest cases. Even if we were able to solve Maxwell's equations for a particular environment, the solution would change completely as soon as the environment changed. In reality, environments change all the time—the antennas may be moving around (on a mobile phone) or scatterers may be changing positions (cars driving past the antennas). Thus, calculating the precise propagation matrix G may not be as useful as asking about the statistical properties of G: What is a "typical" G? What distributions of G's can occur?

These questions are quite similar to those that arise in mesoscopic physics. In the case of mesoscopic disordered metals, we can successfully predict how certain quantities—conductivity or magnetization, for example—vary from one disordered sample to the next. Instead of trying to precisely describe the detailed properties of a particular sample, we study the properties of an ensemble of samples that is fully described by a few parameters, such as the mean free path and the decoherence rate. Analogously, it is useful to describe microwave propagation in a scattering environment in terms of the properties of an ensemble of environments with a few input parameters, such as the mean free path and the absorption length.

Over the years, the analogy between mesoscopic physics and electromagnetic radiation has provided fertile ground for cross-pollination. Ideas about wave interference, which were developed first in the context of mesoscopics, were later pursued intensely in the field of wave propagation. The great flexibility of microwaves as an experimental system allowed for many detailed studies of wave propagation in disordered media.[5,7,8] In thinking about propagation for wireless communications, the analogy to mesoscopia again turns out to be very useful.

As in the case of disordered mesoscopic systems, one can construct a Boltzmann equation for propagation of microwaves[9] analogous to the Boltzmann equation for propagation of electrons. This is just a partial differential equation for the probability density $f(\mathbf{r}, \mathbf{k})$ for having microwaves at position $\mathbf{r}$ moving in direction $\mathbf{k}$. Microwaves traveling in a given direction $\mathbf{k}$ are assumed to have some probability per unit time, denoted by the scattering matrix element $V(\mathbf{k}, \mathbf{k}')$, of being scattered to another direction $\mathbf{k}'$. In many cases, the Boltzmann equation can be further reduced to a simple diffusion equation for microwaves.

An important question in wireless communications is, "If you transmit a given power at one arbitrary point, how much power arrives at another arbitrary point?" The Boltzmann approach answers this question with reasonable accuracy, as shown in figure 2. More important, it gives a simple analytical framework within which to understand propagation problems.

This approach can also address the question of fluctuations in the received power. If you move the receiver from one point to another nearby point, how much will the received power change? It turns out that the received power fluctuates strongly as a function of position. This behavior is analogous to the phenomenon of laser speckle: In both cases, there is a coherent field that is scattered randomly and can interfere with itself either constructively or destructively. Typically, one needs to move the receiver a distance of about half a wavelength to go from a region of constructive to destructive interference. Since the phase of a wave changes by π in a distance $\lambda/2$, the

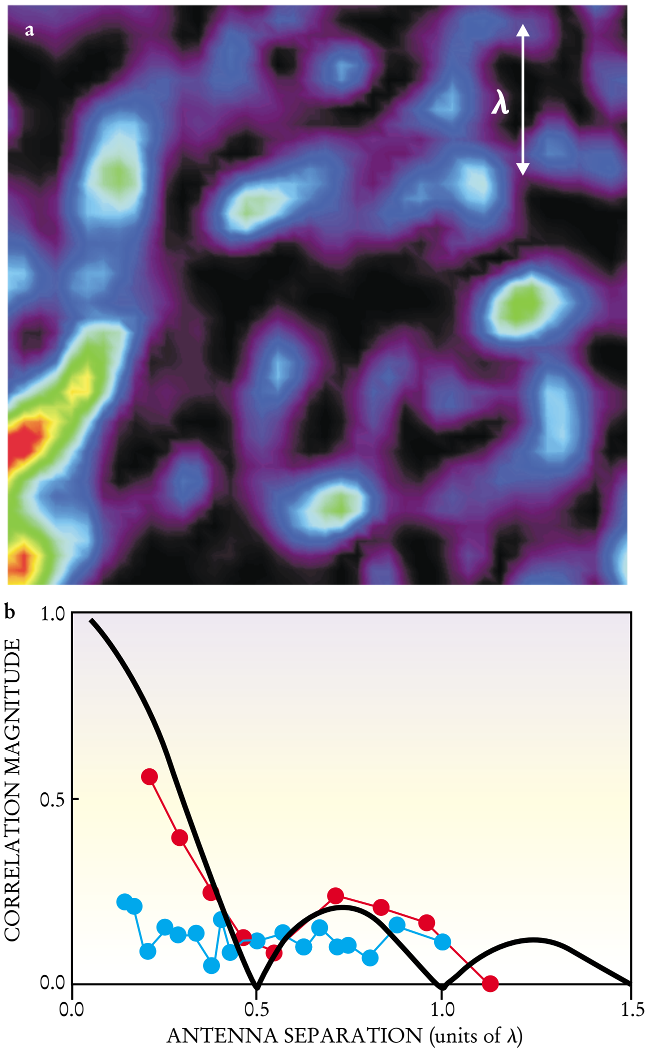

FIGURE 3. MICROWAVE CORRELATIONS in a scattering environment. **(a)** Experimentally received microwave power plotted as a function of position (red is high power, black is low power). Waves traversing different paths interfere to form a speckle pattern. The size of a single speckle (the field correlation length) is of the order of half a wavelength $\lambda/2$ (here $\lambda \approx 12$ cm). **(b)** Magnitude of the correlation of signals received by two antennas as a function of the distance between them, averaged over antenna position and orientation. With omnidirectional antennas (red), the correlation increases with decreasing separation, as might be expected from (a). The black line is the expected field correlation function in an isotropic diffusive environment,[8] $|\sin(2\pi x/\lambda)/(2\pi x/\lambda)|$, which is quite similar to the experimental results of the omnidirectional antennas. But with oppositely facing directional antennas (blue), the correlation stays low even at small separation. For both (a) and (b), transmission was from a single antenna 8–10 m away. (Adapted from ref. 10.)

electric field—which is the sum of contributions of waves coming in randomly from all directions—will change completely in roughly this distance. Conversely, any two points within half a wavelength of each other have highly correlated electric fields. Measurements[5,7,10] of these correlations have been consistent with Boltzmann (or diffusive) modeling, as shown in figure 3. Properly understanding such correlations is critical for multiantenna technology, since the capacity is increased only if the antennas receive uncorrelated signals.

To make these statements about correlations more quantitative, we need to ask specific questions about the properties of the propagation matrix G. Since G depends on the particular environment, we really need to ask about the entire distribution of possible G's that can occur. Mathematically, we can describe this distribution in terms of correlation functions—such as $\langle G_{ij}\rangle$ or $\langle G_{ij}G^*_{kl}\rangle$, where the brackets mean an ensemble average over disorder configurations. For many situations in which scattering occurs, $\langle G_{ij}\rangle$ is zero. However, in general $\langle G_{ij}G^*_{kl}\rangle$ is nonzero. Often, this second-order correlator is sufficient to describe the distribution of G. It turns out that the correlation function $\langle G_{ij}G^*_{kl}\rangle$ is analogous in mesoscopic systems to a conductivity or response function, which is also the average of two Green's functions. Therefore, one can exploit the machinery developed for electronic systems to calculate the properties of G.

Once we know the statistics of G, we may ask, "What is the average information capacity I?" Here, the analogy between information theory and statistical mechanics can be exploited. In statistical mechanics, one often wants to calculate the ensemble average of the log of the partition function. In information theory, we want the ensemble average of the log of a quantity (the determinant in equation 4) that counts the number of states of the system. Making this mapping, one can then use powerful physics techniques, such as random matrix theory, to calculate information capacities.[11] Such calculations are in good agreement with experiment.[10]

Polarization and directional diversity

As we have seen, in a scattering environment, the electric fields at two points are highly correlated if the points are within half a wavelength. Because we want our antennas to receive uncorrelated signals, we might guess that the antennas should be spaced by this distance, which limits the number of independent antennas that can be put on a small device. Still, we would like to use as many independent antennas as possible to increase the information throughput. This apparent conflict can be circumvented by several tricks that allow small devices to carry more antennas.

One proposed approach exploits the multiple polarizations of electromagnetic radiation. With line-of-sight transmission (say, in the x direction), there are two polarizations (y-polarized and z-polarized) that can be used to send two different messages. Unfortunately, since radiation must be polarized perpendicular to its propagation direction, one cannot use x-polarized light to send a signal by line-of-sight in the x direction. However, as shown in figure 4, by bouncing the signal off a scatterer that is far away from the line-of-sight path, one can use the x polarization to send an additional independent signal. Surprisingly, if there is enough scattering in the environment, the three electric and three magnetic polarizations can be transmitted and received independently, allowing the sending of six signals via six different polarizations.[12] One can use this "polarization diversity" to pack up to six independent antennas into a very small region. (This prediction has yet to be verified experimentally because, in practice, it is hard to make small yet sensitive magnetic antennas at cell-phone frequencies.) One might be surprised that the magnetic and electric fields are independent, since from Maxwell's equations, $\mathbf{E} = \mathbf{B} \times \mathbf{k}$. However, such a relation holds only for a single plane wave. If

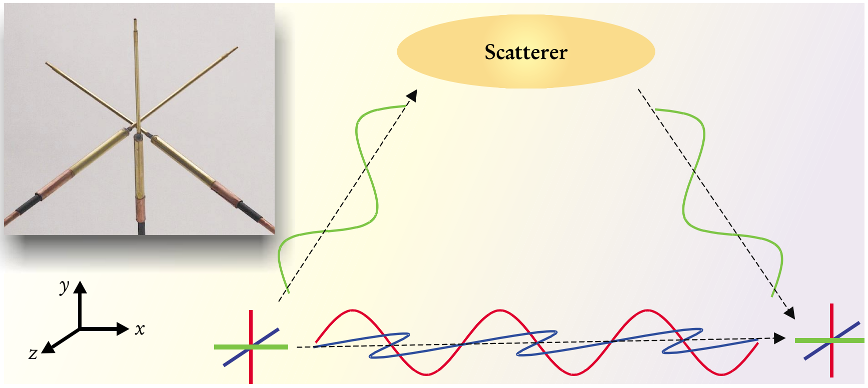

FIGURE 4. TRIPOLE ANTENNAS transmitting and receiving signals in the presence of a single scatterer. In the absence of the scatterer, only the *y*-polarized (blue) and *z*-polarized (red) signals would be received. The presence of the scatterer allows for the additional reception of *x*-polarized signal (green). The result is general, independent of how the tripole antennas are rotated: Without scattering, only two independent signals can be sent from transmitter to receiver; with scattering, a third polarization can be used. (Although not shown, the *y*- and *z*-polarized signals also are partially transmitted through the scatterer.) The inset shows a prototype tripole antenna made of three orthogonal half-wavelength dipoles. (Adapted from ref. 12.)

there are multiple waves incident from different directions, then the sum of the electric fields and the sum of the magnetic fields will be linearly independent.

Another approach that can be used in a highly scattering environment is known as directional diversity. In this approach, one uses a set of antennas that each preferentially see waves coming in from a certain direction. If each antenna is looking in a different direction, the received signals will be independent (see figure 3b) even if the antennas are placed very close together, as in figure 5. Currently, it is still not clear whether there is a fundamental limit to how many independent antennas can be squeezed into a given small volume.

FIGURE 5. COMPACT ANTENNA ARRAY. This prototype array contains four antennas and has an overall size of less than a third of a wavelength. Despite the small size of the array, the individual antennas operate independently due to their directional diversity: In essence, each of these antennas "looks" in a different direction. Such compact antenna arrays may be useful for achieving high information transfer rates in small wireless devices. In a sufficiently rich scattering environment (such as indoors, or in a city), transmission between two sets of these compact antennas can achieve an information transfer rate almost four times larger than single-antenna to single-antenna transmission.

The above approaches are two efficient ways for antennas to exploit independent modes of incoming or outgoing radiation. Such strategies may be extremely valuable for the technology of the future. Whether these particular approaches are actually used on cell phones will depend on many engineering considerations. One thing, however, is certain: The wireless communication industry is growing at an astounding rate, and physics will be playing an essential role in its future. Thinking about multiantenna wireless communication from a physics-based perspective has brought new insight and has already uncovered a number of surprises. Nonetheless, the field is still young and many more surprises are likely still to come.

Many researchers at Lucent Technologies and at Agere Systems are involved in wireless research of the type described in this article. Much of our knowledge of the subject is due to our interactions with these people. In particular we would like to acknowledge Gerry Foschini, Mike Gans, Mike Andrews, Partha Mitra, Rich Howard, and Peter Gammel. Special thanks are due to our collaborators: Harold Baranger, Anirvan Sengupta, and Leon Balents.

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