between nodes is governed by the simplified path-loss model with path-loss exponent $\gamma = 4$. This two-dimensional slice of the 20-dimensional rate region indicates the rates achievable between two pairs of nodes – from node 1 to 2 and from node 3 to 4 – when all other nodes in the network may be used to help forward traffic between these nodes but do not generate any independent data of their own. The figure assumes variable-rate transmission based on the link SINRs, and it plots the achievable rate region assuming single-hop or multihop routing, spatial reuse, power control, and successive interference cancellation. We see a substantial capacity increase by adding multihop routing, spatial reuse, and interference cancellation. Power control does not provide a significant increase, because adaptive modulation is already being exploited and so adding power control as well does not make much difference – at least for this particular network configuration.

Network capacity regions under different forms of cooperative diversity have also been explored [93; 94; 95; 96; 97]. Since the capacity region of a general ad hoc network is unknown, capacity under cooperation has mainly been characterized by lower bounds based on achievable rate regions or upper bounds based on the rate-sum mutual information bound. Results show that cooperation can lead to substantial gains in capacity, but the advantages of transmitter and/or receiver cooperation – as well as the most advantageous cooperative techniques to use – are highly dependent on network topology and the availability of channel information.



## 16.6 Energy-Constrained Networks

Many ad hoc wireless network nodes are powered by batteries with a limited lifetime. Thus, it is important to consider the impact of energy constraints in the design of ad hoc wireless networks. Devices with rechargeable batteries must conserve energy in order to maximize time between recharging. In addition, many interesting applications have devices that cannot be recharged – for example, sensors that are imbedded in walls or dropped into a remote region. Such radios must operate for years solely on battery energy and/or energy that can be harvested from the environment. The $\mu$-AMPs and Picoradio projects are aimed at developing radios for these applications that can operate on less than 100 microwatts and exploit energy harvesting to prolong lifetime [18; 98; 99].

Energy constraints affect the hardware operation, transmit power, and signal processing associated with node operation. The required transmit energy per bit for a given BER target in a noisy channel is minimized by spreading the signal energy over all available time and bandwidth dimensions [100]. However, transmit power is not the only factor in power consumption. The signal processing associated with packet transmission and reception, and even hardware operation in standby mode, consume nonnegligible power as well [24; 101; 102]. This entails interesting energy trade-offs across protocol layers. At the physical layer, many communication techniques that reduce transmit power require a significant amount of signal processing. It is widely assumed that the energy required for this processing is small and continues to decrease with ongoing improvements in hardware technology [24; 103]. However, the results in [101; 102] suggest that these energy costs are still significant. This would indicate that energy-constrained systems must develop energy-efficient processing techniques that minimize power requirements across all levels of the protocol stack and also minimize