# ON ENERGY EFFICIENCY OF ROUTING WITH COOPERATIVE TRANSMISSIONS

by

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## Abstract

Cooperative transmissions emulating multi-antenna systems may help reduce the total energy consumption in wireless networks. In this thesis, we define a virtual multiple-input single-output (vMISO) link to be established when a group of nodes (transmitters) jointly enable space-time communications with a single receiver. There has been plethora of research investigating physical layer issues of such systems; however, higher layer protocols that exploit vMISO links in ad hoc networks are still emerging.

We present a novel approach in characterizing the optimal *multi-hop vMISO routing* in ad hoc networks. The key advantages of vMISO links that we exploit are the increase in transmission range and the decrease in the required transmission energy due to diversity gain. Specifically, under a high node density regime, we solve a nonlinear program that minimizes the total energy cost of reliable end-to-end transmissions by selecting the optimal cooperation set and the location of the next relay node at each hop. We characterize the optimal solution with respect to the reliability of the links, and for different fixed node transmission powers. Our results indicate that a multi-hop vMISO system is energy efficient only when a few nodes cooperate at each hop. We design a new greedy geographical vMISO routing protocol that is also suitable for sparse networks using the results determined under high node density regime.

Also, we consider the network lifetime maximization problem in networks employing vMISO links. We formulated the network lifetime maximization with vMISO routing as a nonlinear program. Then, we presented a novel cooperation set selection and flow augmentation based routing heuristic that can significantly increase the network lifetime compared to Single-Input Single-Output (SISO) systems.

KOOPERATİF İLETİMLERLE YÖNLENDİRMENİN ENERJİ VERİMLİLİĞİ ÜZERİNE

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**Anahtar Kelimeler: enerji verimliliği, işbirliği, yönlendirme.**

## Özet

Çoklu anten sistemlerini örnekleyen kooperatif iletimler, kablosuz ağlarda toplam enerji tüketimini azaltmaya yardım eder. Bu tezde, bir grup göndericinin ve tek bir alıcının birlikte sağladığı, yer-zaman iletişimiyle kurulan sanal çoklu-giriş tekli-çıkış (vMISO) bağlantıları tanımlanmaktadır. Bugüne kadar bu tip sistemleri fiziksel açıdan araştıran birçok çalışma yapıldı, ancak bu sistemleri kullanan daha üst katmanların protokolleri gelişmeye devam ediyor.

Bu tezde, kablosuz tasarsız ağlarda optimal çok-sekmeli vMISO yönlendirmelerinin tanımına yeni bir bakış açısı getiriliyor. Yararlanılan vMISO bağlantıların temel avantajları çeşitliliğin sağladığı iletim menzilindeki artış ve gerekli iletim enerjisindeki azalıştır. Özellikle, düğüm yoğunluğu yüksek olan ağlarda, güvenilir uçtan uca iletimlerin toplam enerji tüketimini, en uygun kooperatif düğüm setini seçerek ve her sekmedeki düğümün yerini belirleyerek en aza indirgeyen lineer olmayan optimizasyon programını çözülüyor. Optimal çözümü bağlantıların güvenirliliğine göre ve değişik sabitlenmiş iletim enerjileri için tanımlanıyor. Alınan sonuçlar gösteriyor ki, çok sekmeli vMISO sistemler her sekmede sadece az sayıda düğüm işbirliğini kullanırsa enerji tüketimi açısından daha çok verim sağlıyor. Bu bilgiler ışığında, seyrek düğümlü ağlar için de uygun olan yeni bir coğrafi vMISO yönlendirme protokolü dizaynı sunuluyor.

Bunlara ek olarak, vMISO bağlantılarını kullanan ağlarda, ağın ömrünün uzatılması problemi üzerinde duruluyor. Bu problemin lineer olmayan optimizasyon programı olarak modellenmesi anlatılıyor. Ayrıca, tekli-giriş tekli-çıkış sistemlerle karşılaştırıldığında ağın ömrünü önemli şekilde arttıran yeni bir işbirliği seti seçme ve bilgi akımı arttırma tabanlı yönlendirme algoritması tanımlanıyor. İncelemelere göre vMISO bağlantılarının ağın ömrünü iki kattan fazla arttırabildiği gösteriliyor.

*to my family..*

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| | | |
|---|---|---|
| SNR | : | Signal-Noise-Ratio |
| SISO | : | Single Input Single Output |
| vMISO | : | virtual Multi Input Single Output |
| vMIMO | : | virtual Multi Input Multi Output |
| BPSK | : | Binary Phase Shift Keying |
| CSI | : | Channel State Information |
| AWGN | : | Additive White Gaussian Noise |
| SER | : | Symbol-Error-Rate |
| STBC | : | Space Time Block Codes |
| ISI | : | Inter-Symbol Interference |
| KKT | : | Karush-Kuhn-Tucker |
| GPS | : | Global Positioning System |
| TTL | : | Time-to-Live |
| TDMA | : | Time Division Multiple Access |

# Chapter 1

## INTRODUCTION

Over the last decade, wireless communication has become an indispensable part of life. Growing demand for various wireless applications has lead to significant development of wireless networks, especially several generations of cellular voice and data networks. The combination of rapid growth at the area of cellular telephony and wireless networking with the Internet has created an environment which implies the desire to imitate the wired networks in a wireless fashion.

More recently, many new applications of wireless networks have emerged. Some of them are ad hoc data networks for wireless sensor, computer, home, and personal networking. A wireless ad hoc network is a collection of wireless nodes that can dynamically self-organize into an arbitrary and temporary topology to form a network without necessarily using any pre-existing infrastructure. Military activities, environmental detection, emergency operations, health monitoring, and disaster recoveries are just a few of innumerable application areas for which ad hoc networks are well suited.

In wireless networks, energy efficiency is a dominating design criterion. In most wireless and especially sensor networks, power is supplied via on-board batteries, which are hard to replace. This thesis studies energy efficiency on wireless networks utilizing cooperation of multiple nodes to generate an array of antenna on the transmit side.

## 1.1 Challenges and Motivations

Improving the wireless link quality is the major problem in wireless networks. Wireless channels are prone to random signal attenuations across space, time and frequency, which is called channel fading. The wireless network also encounters interference problem caused by the transmissions at the shared communication medium. Therefore, problems like reliably transmitting information among radio terminals; mitigating severe channel impairments such as multi-path fading and interference from other users; efficiently allocating and utilizing resources such as power and bandwidth; scaling algorithms as the number of terminals in the network grows; and supporting a large and ever-growing number of applications, such as voice, data, and multimedia networking, occur caused by this challenging environment. These channel distortions require increasing power, bandwidth, and receiver complexity to reliably communicate over longer distances.

On the other hand, in wireless networks where nodes are powered by small batteries that are difficult or impossible to replace, nodes can only transmit a finite number of bits before they run out of energy. Thus, reducing the energy consumption per bit for end-to-end data transmission is an important design consideration for such networks.

A final motivation for the study of energy efficient wireless communications can be found by examining the entire network stack, which traditionally consists of an application layer, followed by the transport and network layers, and finally the physical layer. Unlike the wired systems, layers of the wireless protocol stack cannot be abstracted out from each other to be examined independently, since all layers of the protocol stack affect the energy consumption of each bit simultaneously. Therefore, an efficient system requires a joint design across all these layers that incorporates the underlying hardware characteristics. From this viewpoint, in this thesis, our studies contains cross-layer design of physical and network layers leaving the design of the higher layers of the protocol stack as a future work.

## 1.2 Background on Cooperative Diversity

The multi-path fading is one of the most important limiting factors in the wireless medium. In order to mitigate the effects of fading, the naïve approach is to increase the transmission power so that the average Signal-Noise-Ratio (SNR) is kept above a threshold. Obviously, such a solution is bound to increase the energy consumption of the nodes and decrease the network lifetime.

An intelligent way of overcoming the fading without increasing the transmission power is the spatial diversity which can be achieved by combining the transmissions (or receptions) from multiple antennas (antenna arrays) with appropriate coding and modulation schemes. However the size of multiple antennas pose restrictions in deploying them on mobile terminals (such as the nodes in an ad hoc network).

Cooperative diversity [11] is a recent breakthrough in communication theory that could help in achieving spatial diversity as with the antenna arrays without physically requiring the deployment of such antennas. This can lead to similar benefits as with such antennas and greatly enhance the capacity of an ad hoc network [11]. With cooperative diversity, nodes that are within close proximity of each other would broadcast the same packet at the same time. The signals are then combined coherently at a receiver thereby resulting in significantly enhanced received signal quality. More specifically, one may treat the cooperative transmissions among multiple nodes as a transmission from a virtual node with multiple antennas if certain conditions (time synchronization, channel coding, etc.) are met.

Cooperative diversity is suitable for wireless networks, where the nodes are densely deployed or at least clustered. In particular, transmitter diversity can provide an easy way to reduce the total transmission power needed for long-haul wireless links and improve the quality of point-to-point transmissions. In this thesis, for its implementation simplicity and well developed theory, we consider the diversity achieved by the nodes cooperatively transmitting data to a single destination. Such transmissions will be called virtual Multi Input Single Output (vMISO) transmissions from now on.

The benefits of virtual Multi Input Multi Output (vMIMO) systems at the physical layer have been recently studied in [4,17–19,34,35]. The benefits of using virtual antenna arrays (referred to as cooperative diversity in these efforts) from a theoretical perspective have been shown by Laneman [11]. In particular, Laneman shows analytically that, with two cooperating nodes, full diversity (i.e, diversity of order 2) can be achieved. This implies that the outage probability decays in proportion to the inverse of the square of the SNR ($1/SNR^2$) with cooperative diversity rather than $1/SNR$ which is the rate of decay without cooperative diversity. As the outage probability decreases much faster with an increase in SNR with cooperative diversity, the nodes can communicate over much larger distances reliably, without having to increase their transmission powers.

In light of this fact, several studies have recently explored the use of cooperative diversity as a potential tool to improve the power efficiency of wireless communications [4], [42], [14]. In [4], the authors study the energy efficiency achieved with actual and virtual MIMO systems. It is shown that the energy savings with vMISO systems increase linearly with the distance between the transmitter and the receiver; these savings are achieved with respect to traditional single input single output systems. In [14], the authors provide first indications that cross-layer design considering cooperative diversity may result in significant energy efficiency. In particular, the authors suggest graph theoretical methods for the selection of paths in a randomly constructed network employing cooperative transmissions; they show that their centralized approach can yield energy savings of the order 30-50% over cases wherein no cooperation is used. In [20], Mergen and Scaglione analyzed cooperative diversity in multi-hop networks where the network is sufficiently dense. The authors showed that if the decoding threshold is below a critical value then the message is delivered regardless of the distance between the source and destination.

There has been some work on the use of specialized antennas in ad hoc networks. Most of the work consider the use of steerable or directional antennas wherein the antenna can focus energy in a desired direction. Examples of such efforts may be found in [43], [44], [45], [46] and, [47]. In [43], the author points out that the requirement in terms of the size of antenna arrays could make physical deployment on mobile nodes difficult on the spectral bands in use today. There has been some work on the use of MIMO links in ad hoc networks by Sundaresan and Sivakumar [48, 49]. These studies assume that separate flows are established between the different antenna elements of the sender and receivers to yield a spatial multiplexing gain. The joint use of the antenna elements to provide robustness to fading effects has not been considered. Furthermore, the authors assume that antenna arrays are physically mounted on mobile devices.

One of the critical issues in realizing cooperative diversity in wireless networks is enabling the phase synchronization of cooperative transmissions at the receiver. There have been a lot of efforts on this problem, e.g., [31], [32], [33]. In this thesis, an appropriate synchronization algorithm previously suggested in the literature is assumed to be employed.

Recently, there is an increasing interest in translating the advantages of using vMIMO at the physical layer into higher layer performance benefits, [4], [8], [23]. In [8], the authors develop a new MAC protocol that closely ties in with the underlying physical layer to enable vMISO links, whereas [23] discusses a routing protocol that leverages diversity and multiplexing gains of MIMO links. In both of these works, the main objective is to maximize the network throughput, and the energy efficiency of these protocols is not investigated. In [4], [12] and [9], the energy-efficiency of vMIMO is considered. It is shown that due to additional energy consumption associated with the local information exchange, direct transmission with the vMIMO approach is less efficient than the traditional SISO approach when the transmission distance between source and the destination is below some threshold. In our work, we extend this result to a more realistic case when data can be routed from the source to the destination over multiple hops.

In [3] and [5], multi-hop virtual MIMO schemes based on clustering are also investigated. In both of these works, the objective is to minimize the total energy consumption while satisfying an end-to-end delay bound. In [3], the resulting optimization problem is modeled as a nonlinear integer program, and the authors argue that this problem can be solved by exhaustive search. Unfortunately, the solution of the integer program is not always easily achievable in large-scale networks, and furthermore, the solution does not provide insights into the characteristics of the optimal policy. In [5], the cooperative strategy in [4] is extended to a multi-hop networking setting where the authors determine the routing and scheduling that optimize energy and delay performance based on cooperative MIMO transmissions at each hop. However, their approach is restricted to a double-string network topology representing only regularly spaced sensors for data collection and Alamouti code is used for the transmissions.

In [9] and [3], the authors considered the training overheads of vMIMO systems in addition to the energy-efficiency.

In most of the previously referenced efforts on cooperation in MIMO systems, only diversity gain is considered. However, in [13], the multiplexing gain of vMIMO systems is also considered in addition to the diversity gain, and it is argued that in order to obtain the optimal energy efficiency in vMIMO, both types of gains need to be exploited.

## 1.3 Background on Space-Time Codes

In this section, a brief discussion on space-time codes and the physical layer properties of virtual MISO links is presented. Based on the discussion presented in this section, the energy consumption model for vMISO links will be developed. First, a brief overview of space-time codes and vMISO links is presented; specifically how symbols are encoded and then, transmitted on a multi-element antenna array is addressed. A simple space-time code (the Alamouti code) and later some background on more complex codes is described.

On a vMISO link, multiple transmitters transmit the same symbols to a common destination; this joint transmission improves the signal quality and therefore, the reliability of received information at the destination node. The symbols are *replicated* in *space* and *time* in a specific manner that enables the destination node to combine the received symbols in a simple manner (linear combination) to reap the benefits of *diversity*. Such a replication is performed in blocks of $k$ symbols and is hence referred to as space-time block coding. In the presence of independently flat Rayleigh fading channels between the many transmitters and the receiver, space-time block coding can provide large diversity gains.

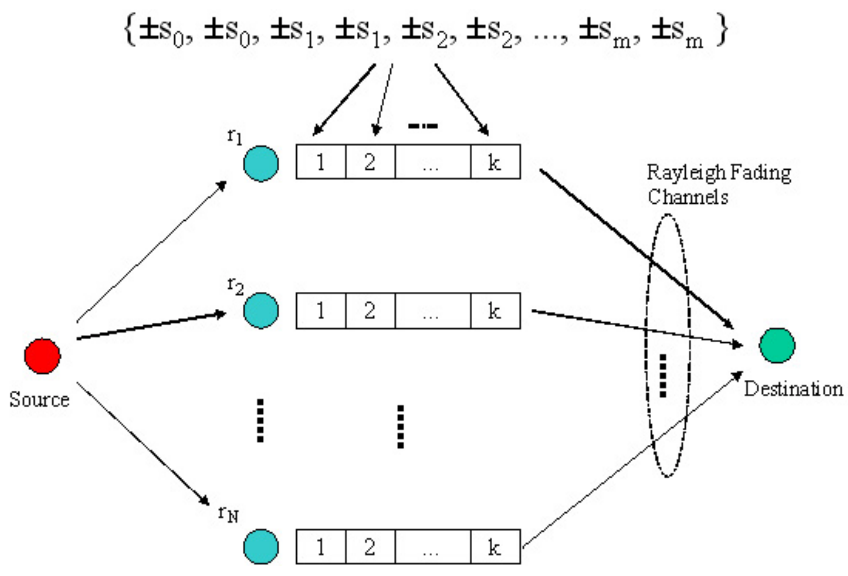


Figure 1.1: Space-Time Block Codes.

### 1.3.1 Space-Time Block Codes

On a virtual MISO link, there are $N$ transmitters that transmit $m$ complex symbols $\pm s_i, \pm s_i^*$ over $kT_s$ seconds as shown in Figure 1.1; here, $s_i^*$ is simply the complex conjugate of the symbol $s_i$ and $m \leq k$. In a SISO system, the single transmitter would send $m$ symbols in $mT_s$ seconds for a symbol rate of $1/T_s$. In the virtual MISO case, the symbol rate will be $\frac{m}{k}\frac{1}{T_s}$. The measure of bandwidth utilization is the *rate* of the space-time block code $R = m/k$. If $m = k$, then, $R = 1$ and the bandwidth is completely utilized; codes that facilitate this are referred to as *full-rate space-time block codes*. In order to ensure that the power used on a virtual MISO link is identical to that over a corresponding SISO link, each transmitter uses only a power $1/N$ times the power of a single transmitter without diversity [6].

Space-time block codes are characterized by a $k \times N$ matrix $\mathbf{S}$ that specifies the *pattern* as per which symbols must be transmitted by the $N$ antennas in each of the $k$ time units of duration $T_s$. The rows correspond to *time* (the times at which the symbols are transmitted) and the columns to *space* (the antenna elements on which they are transmitted). There are basically two different design procedures [6]:

**Complex Orthogonal Design - Alamouti Codes**

Alamouti code is a complex space-time block coding scheme designed for systems with two transmitters and a single receiver [6]. Let $s_1$ and $s_2$ be the symbols to be transmitted from transmitter 1 and transmitter 2 to a single receiver, respectively. Using $2\times2$ Alamouti coding at the transmitters, the transmission matrix $\mathbf{S}$ is defined as,

$$\begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix}$$

With this coding scheme, two symbols are transmitted by two transmitters over $2T_s$ time units: Transmitter 1 transmits the symbols $s_1$ and $-s_2^*$ in $(0, T_s)$ and $(T_s, 2T_s)$, respectively and, transmitter 2 transmits the symbols $s_2$ and $s_1^*$ in the same two time units.

Let $h_i = \alpha_i e^{j\phi_i} + w_i$ be the channel between the transmitter $i$ and the receiver, where $\alpha_i$ is the random attenuation due to fading with Rayleigh distribution, and $w_i$ is the additive channel noise, $i = 1, 2$. The received symbols in the first time unit and the second time unit are $r_1$ and $r_2$, respectively:

$$r_1 = h_1 s_1 + h_2 s_2 \tag{1.1}$$

$$r_2 = -h_1 s_2^* + h_2 s_1^* \tag{1.2}$$

Assuming that the receiver has perfect knowledge of the channel coefficients, the received symbols are linearly combined to achieve diversity gain and the symbols are estimated as:

$$\widetilde{s_1} = h_1^* r_1 + h_2 r_2^*$$

$$\widetilde{s_2} = h_2^* r_1 - h_1 r_2^*$$

which in terms of $s_1,$ and $s_2$ is equal to

$$\widetilde{s_1} = |\alpha_2^2 + \alpha_1^2| s_1 + h_1^* n_1 + h_2 n_2^* \tag{1.3}$$

$$\widetilde{s_2} = |\alpha_2^2 + \alpha_1^2| s_2 + h_2^* n_1 - h_1 n_2^* \tag{1.4}$$

where $n_1, n_2$ are noise components at the receiver and $n_1 = w_1 s_1 + w_2 s_2,\ n_2 = -w_1 s_2^* + w_2 s_1^*$. The diversity gain is due to the fact that the probability that both $\alpha_0$ and $\alpha_1$ will be small due to deep fades at the same time, is low. Alamouti code is the only complex orthogonal space-time block code with rate 1. In addition, as shown above Alamouti code achieves full diversity without requiring channel information at the transmitters.

### Generalized Complex Orthogonal Design

In his pioneering work, Tarokh et al. [24] introduced a methodology for design of generalized complex orthogonal codes applicable to higher orders of diversity. The resulting codes satisfy the condition of complex orthogonality only in the temporal sense; the code rate is less than unity. The transmission matrix $\mathbf{G}$ is an $k-by-N$ matrix consisting of the entries,

$$0, \pm s_1, \pm s_1^*, \pm s_2, \pm s_2^*, ..., \pm s_l, \pm s_m^*,$$

where $m$ is the number of symbols to be transmitted, $k$ is the number of time slots over which symbols are transmitted and $N$ is the number of transmitters. Thus, the rate of such codes is $m/k$. These codes are observed to have low efficiency. To improve the bandwidth efficiency systematic high rate complex orthogonal space-time block codes are proposed [22]. The systematic codes for three and four transmitters are given by the following transmission matrices $G_3$ and $G_4$, respectively.

$$G_3 = \begin{bmatrix} s_1 & s_2 & s_3 \\ -s_2^* & s_1^* & 0 \\ -s_3^* & 0 & s_1^* \\ 0 & -s_3^* & s_2^* \end{bmatrix}$$

$$G_4 = \begin{bmatrix} s_1 & s_2 & s_3 & 0 \\ -s_2^* & s_1^* & 0 & s_3 \\ -s_3^* & 0 & s_1^* & -s_2 \\ 0 & -s_3^* & s_2^* & s_1 \end{bmatrix}$$

The rates of higher diversity systematic codes are given in the following Table 1.1 [22]. With the use of higher order modulation techniques, the bandwidth utilization and bit error rate of low rate codes can be further improved. However, in this thesis, the modulation scheme is assumed to be remain the same for the duration of the system operation.

Table 1.1: High-Rate STBCs from Complex Orthogonal Designs for $2 \leq n \leq 18$ Transmit Antennas [22]

| No. of Transmitters | Rate | No. of Transmitters | Rate |
|---|---|---|---|
| 2 | 1 | 11 | 7/12 |
| 3 | 3/4 | 12 | 7/12 |
| 4 | 3/4 | 13 | 4/7 |
| 5 | 2/3 | 14 | 4/7 |
| 6 | 2/3 | 15 | 9/16 |
| 7 | 5/8 | 16 | 9/16 |
| 8 | 5/8 | 17 | 5/9 |
| 9 | 3/5 | 18 | 5/9 |
| 10 | 3/5 | | |

In this thesis, systematic codes [22] such as those represented by $G_3$ and $G_4$ are used, since these codes have high bandwidth efficiency and their average SNR can be derived in a closed analytical form.

Given that the receiver has perfect knowledge of the channel, the received symbols can be linearly combined as in the case of Alamouti code. For example, for the case of three transmitters $k$th symbol is estimated as:

$$\widetilde{s_k} = |\alpha_3^2 + \alpha_2^2 + \alpha_1^2| s_k + h_1^* n_1 + h_2 n_2^* + h_3 n_3^*, \tag{1.5}$$

and for the case of four transmitters it is estimated as:

$$\widetilde{s_k} \quad = \quad |\alpha_4^2 + \alpha_3^2 + \alpha_2^2 + \alpha_1^2| s_k + h_1^* n_1 + h_2 n_2^* + h_3 n_3^* + h_4^* n_4. \tag{1.6}$$

For higher order diversity, the received signal attains a similar structure, where the square of magnitudes of the channel attenuation are added.

## 1.4 Overview of Contributions

Our main contributions in this thesis can be summarized as follows:

- A realistic channel and energy consumption model taking into account channel fading and transmitter-side cooperative diversity is developed.

- Using the energy consumption model developed, the minimum total energy consumption problem with vMISO links is developed: The characterization of the optimal vMISO routing policies with respect to the number of cooperating nodes, MISO transmission ranges and node transmission powers in very dense networks is developed. The increase in transmission range due to diversity gain is the main advantage of vMISO considered in this thesis, since only MISO systems are considered, the effects of multiplexing gain is not investigated.

- A low complexity greedy position-based vMISO routing algorithm is designed and analyzed: The insights gained with the characterization of the optimal vMISO routing in very dense networks is used to determine an efficient node selection and routing algorithm for sparse networks.

- Using the energy consumption model developed, the maximum lifetime routing problem with vMISO links is defined.

- A low complexity flow augmentation based vMISO routing algorithm is designed and analyzed.

# Chapter 2

## RELIABLE MULTI-HOP ROUTING WITH COOPERATIVE TRANSMISSIONS IN ENERGY-CONSTRAINED NETWORKS

In wireless networks, energy efficiency is a dominating design criterion. In long-range transmissions, transmission energy is the major factor in energy consumption, whereas in short-range transmissions, circuit energy is comparable to or even dominates the transmission energy. Fading, interference and noise in wireless channels further exacerbate the energy consumption of the nodes.

In the physical layer, multiple antenna techniques have been shown to be very effective in improving the performance of wireless systems in the presence of fading [16]. Also, it is well-known that for the same throughput requirement MIMO systems require less transmission energy than SISO systems. An alternative view is that for the same transmission energy MIMO systems can transmit data to further distances than the SISO systems.

However, it is usually infeasible to mount multiple antennas on small wireless devices due to the required size of these antennas. To achieve MIMO gains in wireless networks, cooperative (*virtual*) MIMO techniques have been proposed [11]. These techniques allow multiple nodes in the same vicinity to cooperate in signal transmission and/or reception; thereby, effectively emulating an antenna array.

In this chapter, we define a virtual MISO (vMISO) link to be established when a group of nodes (transmitters) jointly enable space-time communications with a single receiver. For the vMISO link to be formed, the receiver needs to have an estimate of the channel state. We do not assume feedback, i.e., the transmitters do not have any knowledge of the channel state; the diversity benefits are achieved due to the use of space-time block codes (STBC). STBCs are considered attractive because of their linear complexity [16].

The key advantage provided by the vMISO transmission considered in this chapter is the increase in the transmission range while using the same transmission power as in traditional SISO systems. However, due to the additional transmission and electronic energy consumption associated with the local information exchange between the cooperating nodes, the energy efficiency of vMISO compared to the SISO approach is questionable.

Previous work on MIMO transmission techniques usually assumed that the transmission power can be continuously adjusted as needed. However, power control is usually considered difficult in real implementations. Therefore, we consider a more realistic case when all radios transmit at the same fixed power level. For this case, we investigate end-to-end reliable multi-hop vMISO routing strategies that minimize the total energy consumption by selecting the optimal number of cooperating nodes and the vMISO transmission range at each vMISO hop. The end-to-end reliability is achieved by hop-by-hop re-transmissions, i.e., each hop retransmits the lost frames as and when necessary. We analyze the solution of the resulting optimization problem in very dense networks, and identify the characteristics of the optimal vMISO routing strategy as a function of the link symbol-error-rate (SER), the node transmission power and electronic energy costs. Our results indicate that most of the benefits of vMISO transmissions are attained when the number of cooperating nodes is small. Finally, we design a greedy geographical routing algorithm suitable for both sparse and dense networks by using the characteristics of the optimal routing strategy derived for very dense networks.

## 2.1 Channel Model

We assume that the signals are modulated by Binary Phase Shift Keying (BPSK), and transmit antennas do not estimate the channel state information while the receiver has full channel state information (CSI). This is possible by periodic transmission of pilot tones from the source nodes to the destination [9]. We consider a wireless channel with Rayleigh flat fading channels with additive white gaussian noise (AWGN) with zero mean and one-sided spectral density $N_0$. In addition, the signal power is attenuated with a falloff proportional to a constant exponent, $\beta$, of the distance.

In the following, we calculate the minimum required transmission power in a flat-fading channel with SISO, and MISO wireless systems. Each of these systems has to satisfy a minimum average SNR requirement for a given target average symbol-error-rate (SER), $p$.

### SISO System

In a SISO system, there is a single transmitting antenna and a single receiving antenna. Let $s_0(t)$ be the complex envelope of the modulated signal transmitted during the symbol interval $0 \leq t \leq T_s$. Then, the signal received at a node at a distance $d_0$ from the source is:

$$r_0(t) = \alpha_0 e^{j\phi} d_0^{-\beta} s_0(t) + w_0(t), \tag{2.1}$$

where $\alpha_0 e^{j\phi}$ is a complex Gaussian distributed random variable with zero mean and unit variance. Let $w_0(t)$ be the additive channel noise, and $\beta$ be the path loss coefficient which is usually between 2 and 4. The random phase shift, $\phi$, can be estimated when it varies slowly as compared to the symbol duration $T_s$ [12]. Thus, the SNR at the output of the receiver can be calculated as:

$$SNR^{SISO} = \frac{|s_0(t)|^2 d_0^{-\beta}}{|w_0(t)|^2} |\alpha_0|^2 = \frac{P_0}{N_0} |\alpha_0|^2 d_0^{-\beta}, \tag{2.2}$$

where $P_0$ is the symbol power and $N_0$ is the one-sided noise spectral density.

### MISO Systems

In MISO systems, multiple transmit antennas located at the same location transmit data to a single receiver antenna. MISO systems can provide diversity gain over SISO systems due to the transmission of data over multiple independent channels. Thus, when one of the channels is in deep fade, the data can be transmitted reliably over another channel. In order to leverage the benefits of space-diversity, data is encoded by space time block codes (STBC). A STBC with code rate $r_n = k/k_n$ is defined by a transmission matrix with size $k_n \times n$, where $n$ is the number of transmitter antenna elements and $k_n$ is the number of time slots involved in the transmission of $k$ symbols

[6]. Alamouti code is the only STBC with unity rate transmitting two symbols every two time slots [1]. Good performance and computational simplicity of the Alamouti codes motivated the search of similar codes, and in [24], [22], orthogonal STBCs are generated for a higher number of transmitter antennas. The SNR of the received signal at a distance $d_n$ when each of the $n$ co-located antennas transmit with power $P_n/n$ is calculated as [6]:

$$SNR^{MISO} = \frac{P_n}{nN_0} \sum_{i=0}^{n-1} |\alpha_i|^2 d_n^{-\beta}, \tag{2.3}$$

where $\alpha_i$ is the complex Gaussian distributed random variable with zero mean and unit variance characterizing the Rayleigh flat fading channel associated with the $i$th transmitter antenna element. $\alpha_i$ is constant in one STBC block but may vary randomly between blocks.

It is well-known that spatial diversity can help transmit with a lower total energy per symbol, while satisfying the same average symbol error rate (SER) requirement, $p$, [15]. However, since there is no general closed-form expression for SER, it is difficult to quantify the power saving provided by MISO. Thus, many other approaches either have to consider a special case or resort to Monte Carlo simulations [4]. In the following, in order to obtain a convenient expression for the power savings, we consider an approximation where we assume that a transmitted symbol can be successfully decoded when the symbol SNR is above a certain threshold. This approximation provides results close to the results obtained by Monte Carlo simulations [12].

**Lemma 2.1.1 (Power Gain)** The total energy per symbol required by MISO transmission with $n$ antenna elements is $g_n(p)$ times lower than the energy per symbol required by SISO transmission while satisfying the same SER, $p$, and reaching the same distance:

$$g_n(p) = \frac{\gamma_n(p)}{n\gamma_0(p)}, \tag{2.4}$$

where $\gamma_n(p)$ and $\gamma_0(p)$ are such that

$$Pr\left[\sum_{i=0}^{n-1} |\alpha_i|^2 \leq \gamma_n(p)\right] = Pr\left[|\alpha_0|^2 \leq \gamma_0(p)\right] = p. \tag{2.5}$$

**Proof**: [Lemma 2.1.1] Suppose for a target $SER \geq p$, $SNR^{TH}$ is the minimum required SNR for correct decoding at the receiver. Using (2.2), and (2.3),

$$Pr\left[\frac{P_n}{n\,N_0}\sum_{i=0}^{n-1}|\alpha_i|^2 d_0^{-\beta} \leq SNR^{TH}\right] = Pr\left[\frac{P_0}{N_0}|\alpha_0|^2 d_0^{-\beta} \leq SNR^{TH}\right] = p. \quad (2.6)$$

By simple change of variables,

$$Pr\left[\sum_{i=0}^{n-1}|\alpha_i|^2 \leq \gamma_n(p)\right] = Pr\left[|\alpha_0|^2 \leq \gamma_0(p)\right] = p,$$

where

$$\gamma_n(p) = SNR^{TH}\frac{nN_0}{P_n}d_0^{\beta}$$
$$\gamma_0(p) = SNR^{TH}\frac{N_0}{P_0}d_0^{\beta}.$$

For SISO transmission $|\alpha_0|^2$ is a chi-square random variable with 2 degrees of freedom, and $\sum_{i=0}^{n-1}|\alpha_i|^2$ is a chi-square random variable with $2n$ degrees of freedom [25]. Hence, we can calculate $\gamma_0$ and $\gamma_n$ numerically.

In order to attain the same $SNR^{TH}$, transmission power of each antenna in MISO is,

$$\frac{P_n}{n} = P_0\frac{\gamma_0(p)}{\gamma_n(p)}. \quad (2.7)$$

The ratio of the total power for SISO transmission to the total power for MISO transmission gives the power gain, $g_n(p)$:

$$g_n(p) = \frac{P_0}{P_n} = \frac{\gamma_n(p)}{n\gamma_0(p)}. \quad (2.8)$$

□

In Figure 2.1, the power gain, $g_n(p)$, is calculated for varying SER. As demonstrated, increasing $n$ does not yield the same returns in $g_n(p)$ as $n$ gets larger.

Now, assume that instead of using transmitter-diversity to reduce the effective total transmission power, we use it to extend the range of transmission. In particular, assume that all antenna elements transmit with the same power $P_0$. The following lemma establishes the factor by which the transmission range is extended by MISO as compared to SISO.

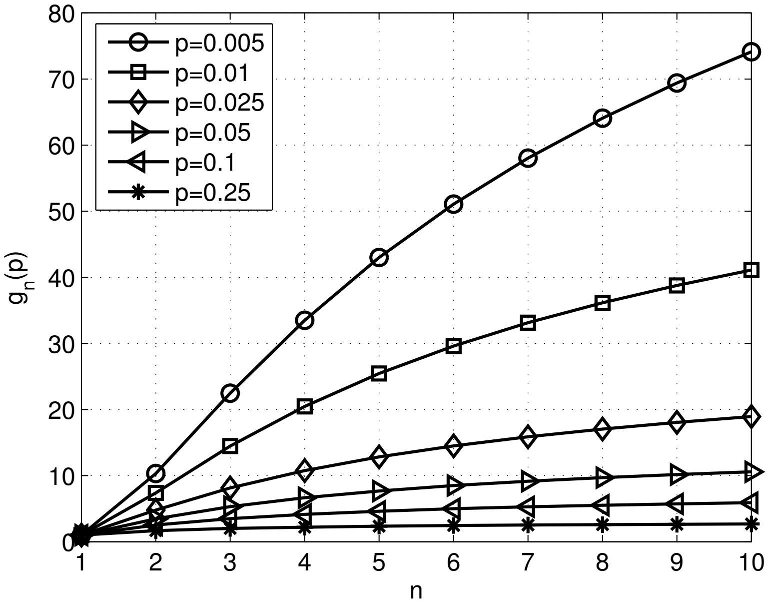


Figure 2.1: Power gain ($g_n(p)$) vs. $n$.

**Lemma 2.1.2 (MISO Distance Extension Factor)** The range of a MISO transmission with $n$ transmitter antennas when each antenna is transmitting with the same power, $P_0$, is extended by a factor of $I_n(p) = (ng_n(p))^{1/\beta}$ as compared to the SISO transmission also with power $P_0$.

**Proof**: [Lemma 2.1.2] Suppose for a target $SER \geq p$ the minimum required SNR is $SNR^{TH}$, then,

$$\gamma_n(p)\frac{P_n}{nN_0}d_n^{-\beta} = \gamma_0(p)\frac{P_0}{N_0}d_0^{-\beta} \tag{2.9}$$

$$d_n = \left(\frac{\gamma_n(p)}{n\gamma_0(p)}\frac{P_n}{P_0}\right)^{1/\beta} d_0, \tag{2.10}$$

where $P_n$ is the total transmission power of MISO.

When $P_n/n = P_0$ and $g_n(p) = \frac{\gamma_n(p)}{n\gamma_0(p)}$,

$$d_n = (ng_n(p))^{1/\beta} d_0. \tag{2.11}$$

□

### 2.1.1 Energy Consumption Model

We adopt the energy consumption model in [7]. Let $E_a = 100pJ/bit/m^{-\beta}$ be the energy consumed to transmit a single bit to a unit distance where $\beta$ is the path loss

Table 2.1: Energy consumption parameters

| | |
|---|---|
| $E_e^t$ | $50nJ/bit$ |
| $E_e^r$ | $50nJ/bit$ |
| $E_a$ | $100pJ/bit/m^{-\beta}$ |
| $E_a'$ | $100d_{nom}^{\beta}pJ/bit$ |

coefficient. Also, let $E_e^t = E_e^r = 50nJ/bit$ be the energy consumed by transmitter and receiver circuitry, respectively. We assume that all transmissions are made at the same power level, $P_0$, which is the sufficient power to transmit reliably with a SISO system to a distance of $d_{nom}$ meters when SER is $p_{nom}$. The corresponding transmission energy cost is given as $E_a' = 100d_{nom}^{\beta}pJ/bit$. When it is required to transmit with a different SER, $p$, the new SISO transmission range is determined by

$$d_0(p) = d_{nom}\left(\frac{\gamma_0(p)}{\gamma_0(p_{nom})}\right)^{1/\beta}. \tag{2.12}$$

We neglect the energy consumption due to the periodic transmission of the pilot signals, since these signals take very short duration and the pilot signals are also used in other wireless systems that do not employ cooperative transmissions [6].

## 2.2 Energy Efficiency of vMISO Routing

In vMISO systems, a collection of cooperating nodes emulate the antenna array of real MISO systems. There is a single *head node* in this cluster that is the originator of data, and there are multiple *cooperating nodes*. Unlike real MISO systems, antennas are not co-located in vMISO systems. Therefore, the head node first transmits the original data to the cooperating nodes. Then, each node in the cluster simultaneously transmits the symbols of the selected STBC transmission block to a receiver. Before cooperative transmission, cooperating nodes can synchronize their carrier frequency and symbol timing to their received signals when the head node transmits the original data. If the maximum distance between the head node and the cooperating nodes is $d_0$, then the beginning time of the cooperative transmission at the head node is up to $d_0/c$ seconds earlier than the cooperating nodes, where

$c$ is the speed of light. In the worst case, the signals transmitted by the nodes in the cluster arrive at the receiver with a relative delay of $2d_0/c$. These delays may cause synchronization errors in both carrier and timing phases. Li *et. al.*, [12], argue that the maximum distance between the cooperating nodes must be chosen small enough to reduce the worst-case delay between arriving signals at the receiver, and, thus, to bring down the inter-symbol interference (ISI) to a negligible level. The authors show that for a symbol period of $T = 10^{-6}$ sec, the maximum distance between cooperating nodes, $d_0$, should be less than 10 meters in order for the delay between the received signals to be 15 times less than $T$, and for ISI to be less than 0.06. Therefore, when $d_0$ is selected to be sufficiently small, then the performance degradation due to synchronization errors can be neglected. We omit the delays due to processing, and thus, traditional STBC can be applied directly.

In order to facilitate vMISO transmissions in wireless networks a new MAC protocol should also be developed. One such protocol was discussed in detail in [8]. In this work, we do not elaborate on the MAC layer issues and focus on the cross-layer design of the network and physical layers.

In the following, we first determine the energy efficiency of vMISO routing under a *high node density regime*, where there are infinitely many nodes in the network. Thus, a head node can always find cooperating nodes that are arbitrarily close to itself. In this case, the results of Lemma 1 and 2 are applicable to vMISO as well. We first determine, in Section 2.2.1, the conditions under which a direct extended range vMISO transmission is more energy efficient then the multi-hop SISO transmissions. Later, in Section 2.2.2, we determine the optimal multi-hop vMISO routing strategy. Both of these strategies are used to design a practical routing algorithm in Section 2.3.

### 2.2.1 Single-Hop vMISO vs. Multi-Hop SISO

We first compare the energy efficiency of direct vMISO transmission and multi-hop SISO transmission. Let $E_{vMISO}(k, d_n, n)$ be the total energy cost of transmitting $k$ bits of information to a distance of $d_n$ in a single vMISO transmission, given that there are $n$ cooperating nodes. As discussed above, vMISO transmission consists of two phases. In the first phase, the head node *broadcasts* data to the cooperating nodes by a SISO transmission, and in the second phase, all nodes collectively transmit data to the receiver node. Let $E^{Ph1}(k,n)$ and $E^{Ph2}(k,n)$ be the energy consumed in the first and second phases, respectively. In the first phase, the head node consumes $E_{src}(k)$ units of energy to broadcast $k$ bits to its cooperating neighbors with a constant transmission power $P_0$. Note that when SER is $p_{nom}$ all cooperating nodes should lie within $d_{nom}$ units of distance from the head node. We assume that SISO transmission in the first phase is always reliable. In addition, $n-1$ cooperating nodes consume $E_{rs}(k,n)$ units of energy in total to receive $k$ bits from the head node.

$$E^{Ph1}(k,n) = E_{src}(k,d_0) + E_{rs}(k,n), \tag{2.13}$$

$$E_{src}(k) = kE_e^t + kE_a', \tag{2.14}$$

$$E_{rs}(k,n) = k(n-1)E_e^r. \tag{2.15}$$

In the second phase, each node that is involved in cooperation transmits the bits to the receiver according to an appropriate STBC with a code rate $r_n = k/k_n$. Each cooperating node consumes a processing energy to encode the symbol, and transmits $k_n$ bits again with the same transmission power $P_0$. While transmitting $k_n$ bits, each node consumes a total energy of $k_n E_e^t$ in the transmitter circuitry and $k_n E_a'$ in the transmitter amplifier. The range of the vMISO transmission when SER is $p$, is $d_n(p) = I_n(p)d_0(p)$, where $I_n(p)$ is calculated in Lemma 2.1.2. Hence, the total energy consumption of the cooperating nodes, $E_{coop-set}(n)$, and the destination node, $E_{dest}(n)$, are calculated from (2.17),(2.18).

$$E^{Ph2}(k,n) = E_{coop-set}(n) + E_{dest}(n), \tag{2.16}$$

$$E_{coop-set}(n) = nk_nE_e^t + E_a'nk_n, \tag{2.17}$$

$$E_{dest}(n) = k_nE_e^r. \tag{2.18}$$

From (2.14), (2.15), (2.17), and (2.18), $E_{vMISO}(k,d_n,n)$ is given as,

$$\begin{aligned} E_{vMISO}(k,d_n,n) &= E^{Ph1}(k,n) + E^{Ph2}(k,n) \\ &= kE_e\left[n + \frac{E_a'}{E_e} + \frac{1}{r_n}\left(n(1+\frac{E_a'}{E_e}) + 1\right)\right], \end{aligned} \tag{2.19}$$

when $E_e^t = E_e^r = E_e$.

In case of MISO transmissions, since all antennas are located at the same node, the first phase in vMISO transmissions is missing in MISO transmissions. Thus, a MISO transmission consumes an energy, $E_{MISO}(k, d_n, n)$, while transmitting $k$ bits to a distance $d_n$ with SER, $p$:

$$E_{MISO}(k, d_n, n) = kE_e \left[ \frac{1}{r_n} \left( n(1 + \frac{E'_a}{E_e}) + 1 \right) \right], \tag{2.20}$$

when $E_e^t = E_e^r = E_e$.

Similarly, a SISO transmission consumes an energy, $E_{SISO}(k, d_0)$, while transmitting $k$ bits to a distance $d_0(p)$ with SER, $p$:

$$E_{SISO}(k, d_0) = kE_e^t + kE'_a + kE_e^r. \tag{2.21}$$

Note that vMISO transmissions reach a distance of $d_n = I_n(p)d_0(p)$, while consuming $E_{vMISO}(k, d_n, n)$ amount of energy. If SISO transmissions are used to reach the same distance, $d_n(p)$, there should be at least $\lceil I_n(p) \rceil$ number of SISO hops. Thus, the total energy consumed with multi-hop SISO is,

$$\begin{aligned} E_{SISO}(k, d_n) &= \lceil I_n(p) \rceil E_{SISO}(k, d_0), & (2.22) \\ &= \lceil I_n(p) \rceil \left( kE_e^t + kE'_a + kE_e^r \right). & (2.23) \end{aligned}$$

**Theorem 2.2.1 (Efficiency of direct vMISO transmission)** When there are $n-1$ cooperating nodes, a direct vMISO transmission consumes less energy than the multi-hop SISO system, if

$$\left\lceil (n g_n(p))^{1/\beta} \right\rceil > \frac{n + \frac{E'_a}{E_e} + \frac{1}{r_n}\left( n + 1 + n\frac{E'_a}{E_e} \right)}{2 + \frac{E'_a}{E_e}}, \tag{2.24}$$

where $E_e^t = E_e^r = E_e$.

**Proof**: [Theorem 2.2.1] Comparing total energy consumptions of both cases using (2.23) and (2.19),

$$E_{vMISO}(k, d_n, n) < E_{SISO}(k, d_n)$$

$$E_{vMISO}(k, d_n, n) < \lceil I_n(p) \rceil E_{SISO}(k, d_0)$$

$$n + E'_a/E_e + \frac{1}{r_n}\left( n + 1 + nE'_a/E_e \right) < \lceil I_n(p) \rceil \left( 2 + E'_a/E_e \right),$$

where $E_e^t = E_e^r = E_e$. □

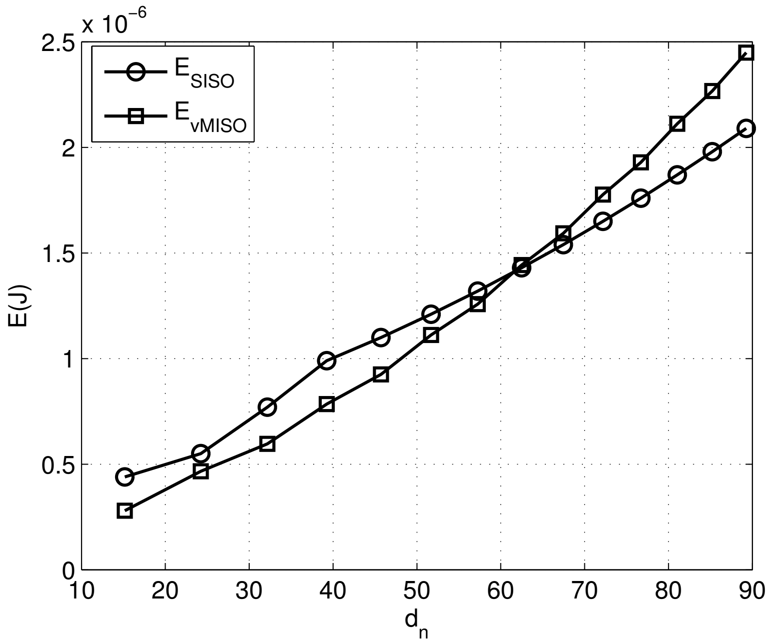


Figure 2.2: Energy efficiency of single hop vMISO over multi-hop SISO, when $d_{nom} =$ 10m, $p = 0.025$ and $\beta = 2$.

In Figure 2.2, we compare the energy consumptions of the multi-hop SISO and the single-hop vMISO for varying $d_n(p)$ when SER is $p = 0.025$. Each point on the lines represents $d_n(p)$, for $n = 1, 2, \ldots$, respectively. According this figure, single-hop vMISO has lower energy cost than the multi-hop SISO when $n \leq 9$ and $d_n(p) \leq 62$m.

### 2.2.2 Multi-Hop vMISO vs. Multi-Hop SISO

Now, we consider the case where a destination $D$ meters away is reached via multiple vMISO hops. Our objective is to find the optimum number of vMISO hops, and the corresponding optimum number of cooperating nodes at each hop that minimizes the total energy consumption. Again, we solve this problem under a high node density regime. In order to determine a closed-form solution, we approximate the STBC code rate, $r_n$, and the power gain, $g_n(p)$, with closed-form functions. The approximated versions of the code rate, $\widetilde{r}_n$ and the power gain, $\widetilde{g}_n(p)$ are given as,

$$\begin{aligned}\widetilde{r}_n =& \; a_1 n^{-b_1}, \\ \widetilde{g}_n(p) =& \; a \log(n) \exp(-bp) + c \log(n) + d \exp(-fp) + h.\end{aligned}$$

The values for the parameters in these functions are given in Tables 2.2 and 2.3. In Figure 2.3, we depict the exact and approximate values for the STBC code rate,

Table 2.2: Approximation parameters for $r_n$

| Parameter | $a_1$ | $b_1$ |
|---|---|---|
| Value | 1.12 | 0.29 |

Table 2.3: Approximation parameters for $g_n(p)$

| Parameter | $a$ | $b$ | $c$ | $d$ | $f$ | $h$ |
|---|---|---|---|---|---|---|
| Value | 45.34 | 119.24 | 2.50 | -38.57 | 123.34 | 0.96 |

$r_n$, and the power gain $g_n(p)$ with respect to varying number of cooperating nodes, $n$. The exact values of $r_n$ are taken from [24]. When $1 \leq n \leq 10$, the mean square error of $\widetilde{r}_n$ and $\widetilde{g}_n(p)$, are 0.001497 and 4.280017 for $p = 0.01$, respectively.

Under a high node density regime, and when $n$ is assumed to take real values, the *optimal number of cooperating nodes*, $n_{opt}$ is the same at each hop by symmetry, and the distance covered at each hop is $d_{n_{opt}}(p) = \left(n_{opt} g_{n_{opt}}(p)\right)^{1/\beta} d_0(p)$.

**Lemma 2.2.2 (Number of hops in multi-hop vMISO)** Let $M$ and $K$ be the number of hops needed to transmit a symbol to a distance of $D$ with multi-hop SISO and vMISO systems, respectively. Then, $K$ is lower bounded by,

$$K \geq (M-1)\left(n g_n(p)\right)^{-1/\beta}. \tag{2.25}$$

**Proof**: [Lemma 2.2.2] Note that $M\, d_0(p) \geq D$ and $K\, d_n(p) \geq D$. By Lemma 2.1.2, and noting that $M \in \mathbb{Z}^+$ and $\frac{D}{d_0(p)} \leq M \leq \frac{D}{d_0(p)} + 1$,

$$K\, d_0(p)\left(n g_n(p)\right)^{1/\beta} \geq D \tag{2.26}$$

$$K \geq \left(n g_n(p)\right)^{-1/\beta} D/d_0(p) \tag{2.27}$$

$$K \geq (M-1)\left(n g_n(p)\right)^{-1/\beta}. \tag{2.28}$$

□

The total energy consumption of transmitting $k$ bits to a distance of $D$ meters with a multi-hop SISO, and a multi-hop vMISO system with $n$ cooperating nodes

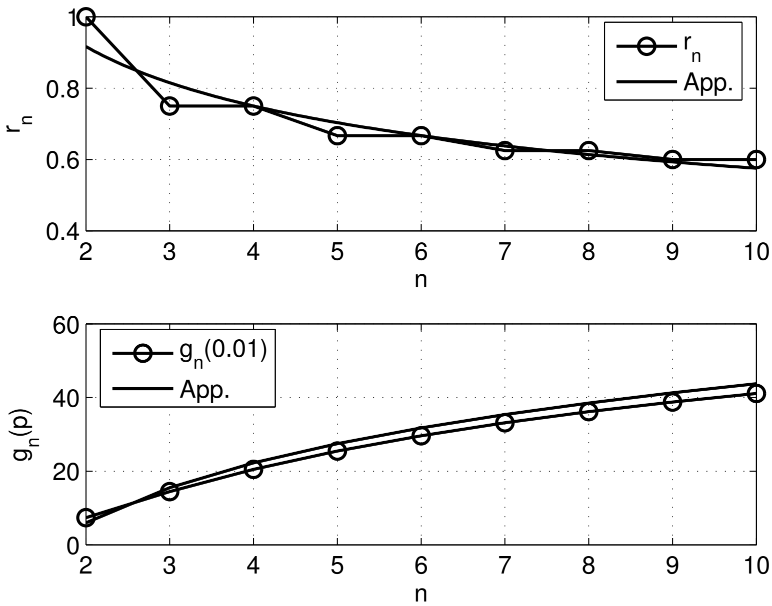


Figure 2.3: Exact and approximate values of code rate $r_n$ and power gain $g_n(p)$ versus $n$.

are given by,

$$E_{SISO}(k, D) = M\, E_{SISO}(k, d_0) \tag{2.29}$$

$$E_{vMISO}(k, D, n) = K\, E_{vMISO}(k, d_n, n) \tag{2.30}$$

$$E_{MISO}(k, D, n) = K\, E_{MISO}(k, d_n, n). \tag{2.31}$$

Note that the number of hops with MISO is the same as the number of hops with vMISO since their transmission ranges are equal.

We first determine the optimal number of cooperating nodes per vMISO hop, $n$, and the optimal number of antennas per node per MISO hop, $n$, when the required reliability for each transmission, SER, $p$, is given. Later, we will jointly optimize $n$ and $p$ in order to obtain the most energy efficient and reliable design.

### Optimal number of cooperating nodes in vMISO given SER

Our objective is to minimize the total energy consumption of vMISO by defining the optimal number of cooperating nodes at each hop for a given SER requirement,

$p$. The optimization problem is defined as,

$$\min_{n} E_{vMISO}(k, D, n) = K\, E_{vMISO}(k, d_n, n) \tag{2.32}$$

s.t.

$$n \geq 1, \tag{2.33}$$

$$K \geq (M-1)\left(n g_n(p)\right)^{-1/\beta} \tag{2.34}$$

Note that $n$ and $K$ are nonnegative integers, and thus, (2.32)-(2.34) is a nonlinear integer program. Although numerical solution techniques exist for such problems, in order to obtain an insight on the optimal solution, we choose to relax the integrality condition and solve (2.32)-(2.34) for $n \in \mathbb{R}^+$, and $K \in \mathbb{R}^+$. The following theorem establishes the optimal cooperating strategy with respect to path loss coefficient and SER requirements.

**Theorem 2.2.3 (Optimum cooperating set size)** The optimum number of cooperating nodes, $n_{opt}$, that minimizes the total energy consumption of vMISO is greater than two, i.e., $n_{opt} > 2$, for $p_{nom} = 0.1$, $d_{nom} = 10$m, when

1. $\beta = 2$ and $0 \leq p \leq 1$,
2. $\beta = 3$ and $p \leq 0.026$,
3. $\beta = 4$ and $p \leq 0.016$.

**Proof**: [Theorem 2.2.3] Let $E = E_{vMISO}(k, D, n)$. Using (2.30) and (2.19), $E$ is written as,

$$E = K\, k\, E_e \left[ n + \alpha + \frac{1}{r_n}\left(n(1+\alpha)+1\right) \right], \tag{2.35}$$

where $\alpha = E'_a/E_e$, and $K$ is the number of hops needed with vMISO transmissions.

Using Lemma 3, we substitute $K = (M-1)\left(n g_n(p)\right)^{-1/\beta}$ into (2.35),

$$E = (M-1)(n g_n(p))^{-1/\beta} k\, E_e \left[ n + \alpha + \frac{1}{r_n}\left(n(1+\alpha)+1\right) \right].$$

Let $E' = \frac{E}{k\, E_e (M-1)}$. Then, since $k$, $E_e$ and $(M-1)$ are nonnegative constants, minimizing $E$ is equivalent to minimizing $E'$. Also note that the optimal solution

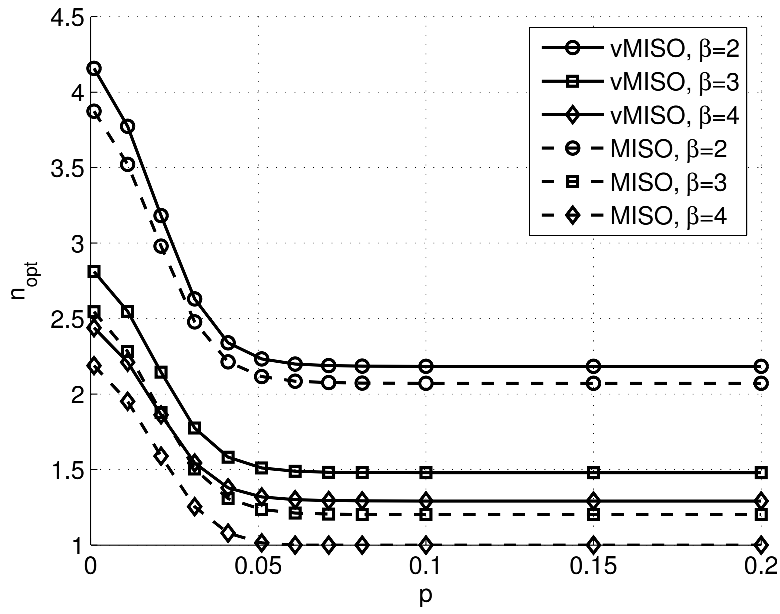


Figure 2.4: The optimal number of cooperating nodes,$n_{opt}$, vs. required SER, $p$, for varying $\beta$.

occurs when (2.34) is satisfied with equality. Then, the equivalent optimization problem is,

$$\min_{n} \; E' = (ng_n(p))^{-1/\beta}\left[n + \alpha + \frac{1}{r_n}\left(n(1+\alpha)+1\right)\right]$$
$$s.t \;\; 1 - n \leq 0.$$

We solve this optimization problem by lagrangian optimization, where $L(n, \lambda)$, and $\lambda$ are the Lagrangian function and multiplier, respectively.

$$L(n, \lambda) = E' + \lambda(n-1). \tag{2.36}$$

Karush-Kuhn-Tucker (KKT) conditions [26] give the first order optimality conditions for $n_{opt}$.

$$\frac{\partial L(n,\lambda)}{\partial n} = \frac{\partial E'}{\partial n} + \lambda\frac{\partial(1-n)}{\partial n} = 0,$$
$$\lambda[n-1] = 0, \;\; \lambda \geq 0.$$

The numerical solution of KKT conditions gives the desired result. □

In Figure 2.4, we calculated $n_{opt}$ in vMISO and MISO systems for varying link SER, $p$. In MISO case, $n_{opt}$ corresponds to the optimal number of antennas per node. In this figure, it is observed that cooperation is especially preferred when the required link SER is low. For high SER, $n_{opt}$ decreases, and converges to an horizontal asymptote. This is because, for lower SER values, the range of a SISO transmission is very short, and thus, a large number of hops is needed to reach the destination. In this case, using vMISO transmissions with a high number of cooperating nodes can increase the transmission range significantly, thereby reducing the number of hops which in turn reduces the total energy cost. However, for higher SER values, the range of SISO is sufficiently long, and thus, additional cooperation among nodes does not yield much benefit. The asymptote is reached when $p \approx 0.1$, because for $p > 0.1$, $g_n(p)$ remains approximately constant as demonstrated in Figure 2.1. Also note that $n_{opt}$ is lower for higher $\beta$, since the transmission energy is increased with increasing $\beta$, and this is compensated by lower $n_{opt}$. Comparing with the $n_{opt}$ in MISO case, $n_{opt}$ in vMISO is slightly larger. This is because, the local information exchange phase in vMISO systems makes vMISO use higher number of nodes to decrease the number of hops taken to compensate the energy consumption due to the first phase. However, in MISO transmissions there is no local information exchange phase and the energy cost of a MISO transmission is less affected by the number of cooperating antennas than in vMISO case. Thus, for minimum energy consumption, a MISO transmission needs lower number of antennas.

### Jointly optimal number of cooperating nodes and link reliability

Now, we additionally consider the end-to-end reliability of the transmissions. If a transmission fails on a link, it is re-transmitted. Let $rt(p)$ be the probability of re-transmission on a link when SER is $p$. Link failure is presumed to be independent and unpredictable, so our objective is to minimize the total *average* energy cost by determining the jointly optimal number of cooperating nodes, $n_{opt}$, and the optimal target SER, $p_{opt}$, at every hop. Under the high node density regime, and when $n \in \mathbb{R}^+$, $n_{opt}$ and $p_{opt}$ would be the same at every hop by symmetry.

The total average energy cost of multi-hop vMISO and MISO are,

$$\mathbf{E}\left[E_{vMISO}(k, D, n, p)\right] = \tfrac{K}{1-rt(p)} k\, E_e \left[n + \tfrac{E'_a}{E_e} + \tfrac{1}{r_n}(n(1 + \tfrac{E'_a}{E_e}) + 1)\right], \quad (2.37)$$

$$\mathbf{E}\left[E_{MISO}(k, D, n, p)\right] = \tfrac{K}{1-rt(p)} k\, E_e \left[\tfrac{1}{r_n}(n(1 + \tfrac{E'_a}{E_e}) + 1)\right], \quad (2.38)$$

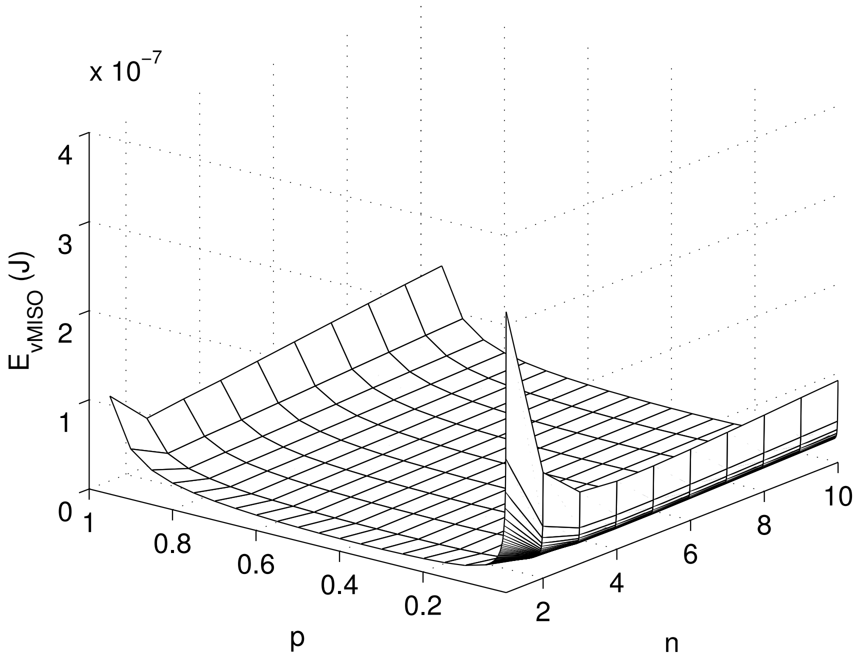


Figure 2.5: The total average energy consumption of multi-hop vMISO, $E_{vMISO}$

where $D$ is the distance between the source and the destination, $K = D/d_n(p) = \frac{D}{d_0(p)(ng_n(p))^{1/\beta}}$ is the number of vMISO and MISO hops, and $d_0(p)$ is given by (2.12).

Figure 2.5 and Figure 2.6 demonstrate $E_{vMISO}$ and $E_{MISO}$, respectively, when $k = 1$, and $rt(p) = p$. It is easy to show that $E_{vMISO}$ and $E_{MISO}$ are a quasi-convex functions, and thus, a globally optimum solution can be determined for both of them.

In Figure 2.7, $n_{opt}$ is calculated for varying values of $d_{nom}$ and $\beta$ for MISO and vMISO systems. Note that by increasing $d_{nom}$ for a given $p_{nom}$, we equivalently increase the fixed node transmission power, $P_0$. From this figure, for vMISO systems, it is observed that, while $d_{nom}$ is increasing $n_{opt}$ also increases until it converges to a horizontal asymptote. This is because, everything else remaining the same, increasing $d_{nom}$ increases the energy cost. In order to reduce the increasing energy cost, larger $n$ can be used to increase the vMISO range, and thus decrease the number of hops. However, increasing $n$ also reduces the transmission rate, and causes an increased number of symbol transmissions. Thus, there is a threshold beyond which increasing $n$ no longer reduces the energy cost. On the other hand, in MISO case, we see a decay in the optimum number of antennas while $d_{nom}$ is increasing. The

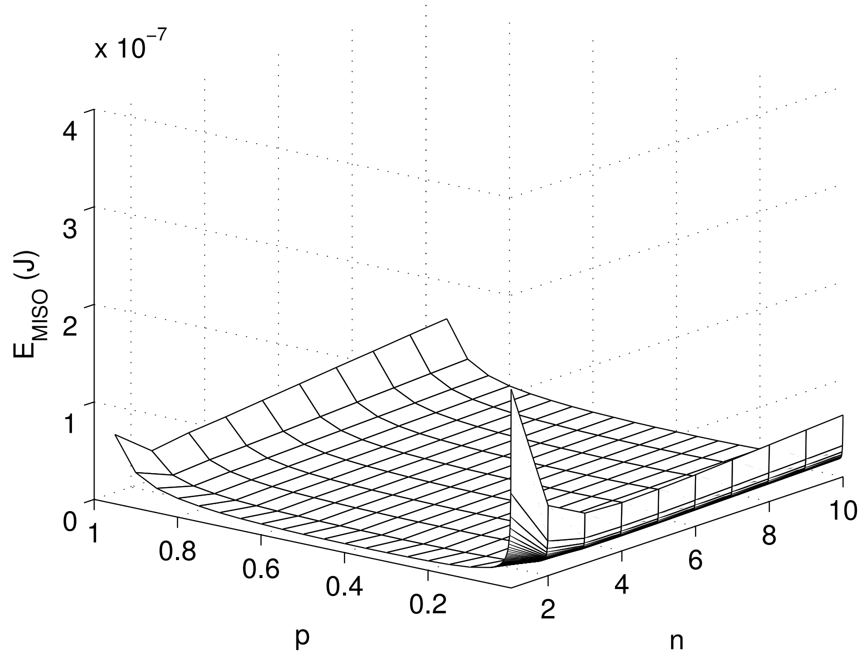


Figure 2.6: The total average energy consumption of multi-hop MISO, $E_{MISO}$

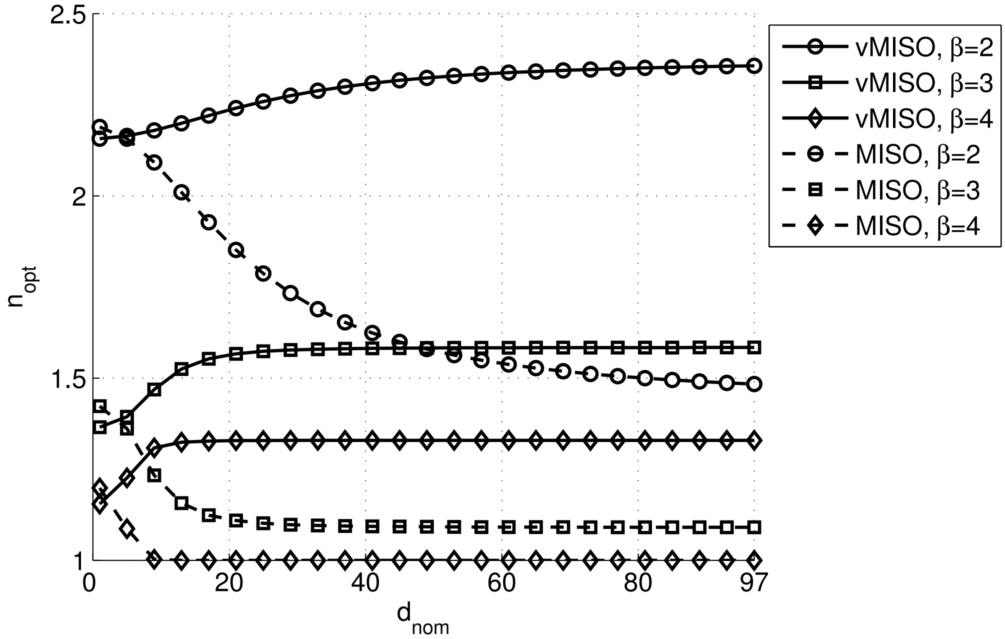


Figure 2.7: The optimal number of cooperating nodes, $n_{opt}$, vs. $d_{nom}$

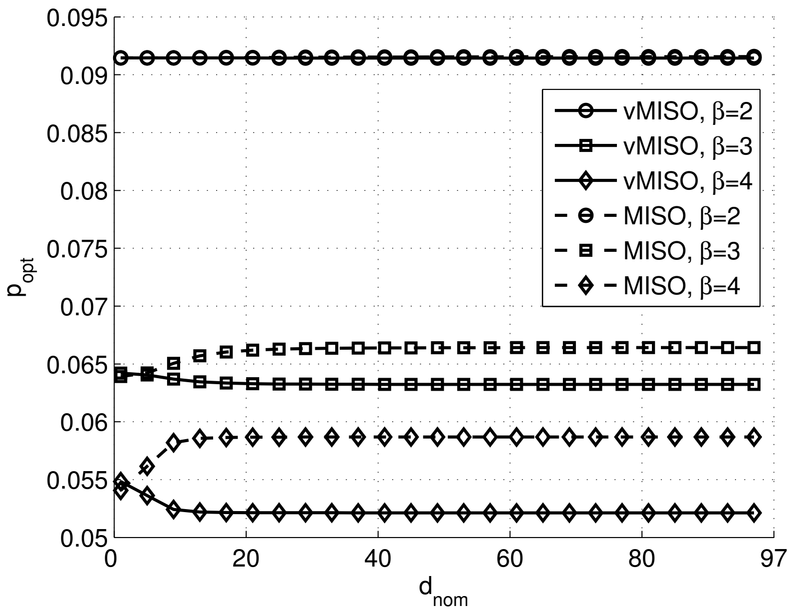


Figure 2.8: Optimal SER, $p_{opt}$, vs. $d_{nom}$

increase in $d_{nom}$ means that the transmission range of SISO increases also. Since there is no local information exchange phase in MISO systems, and the more the number of antennas the more energy is consumed, while $d_{nom}$ is increasing it is better to have less number of antennas. However, in vMISO, since there is a local information exchange phase, more number of cooperating nodes has to be used to compensate the energy consumption in the first phase by decreasing the number of hops taken more than in MISO systems.

In Figure 2.8, $p_{opt}$ is calculated for varying values of $d_{nom}$ and $\beta$. In this figure, we again observe that for each $\beta$ value, $p_{opt}$ converges to a horizontal asymptote as $d_{nom}$ increases. The explanation of this behavior is similar to that of Figure 2.7.

Finally, in Figure 2.9, the logarithm of the minimum energy cost $E$ is given for varying values of $d_{nom}$ for vMISO and MISO systems. For both of the transmission models, it is observed that there is an optimal $d_{nom}$ value for which the energy cost is the minimum, and the explanation is the same. Note that higher node transmission powers result in longer vMISO transmission range, and thus decrease the number of hops to the destination. This has a decreasing effect on the total vMISO multi-hop transmission energy. However, increasing the transmission power also increases the energy cost per transmission. Therefore, there is a trade-off between a high $d_{nom}$

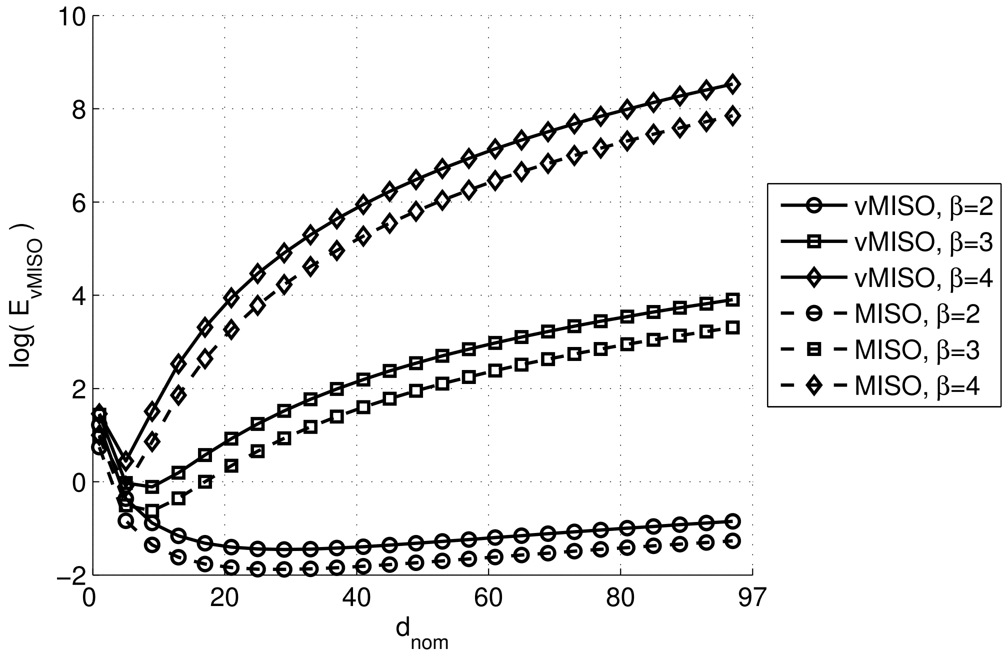


Figure 2.9: Logarithm of the minimum energy cost, $E_{vMISO}(k, D, n_{opt}, p_{opt})$, vs. $d_{nom}$

value and the total vMISO energy cost. In Figure 2.9, the optimal $d_{nom}$ is found to be 25, 7 and 5 for $\beta = 2$, $\beta = 3$, and $\beta = 4$, respectively. The reason for this decrease in the value of the optimal $d_{nom}$ is that increasing $\beta$ increases the energy cost exponentially. Thus, in order to compensate for this increase in the energy cost, $d_{nom}$ should be reduced.

Also, in Figure 2.9, it is demonstrated that MISO systems consume less energy than vMISO systems. This is again due to the missing local information exchange phase in MISO systems.

Note that the results in Figures 2.7, 2.8, and 2.9 depend on the re-transmission probability $rt(p)$. The re-transmission probability in turn depends on the packet size, the type and the rate of the error correcting codes (ECC) used. There are numerous previous works on determining the packet size and ECC rate optimizing a relevant user or network performance metric such as throughput or energy. In this paper, we do not investigate the optimization of $rt(p)$ further and leave this subject for future work.

## 2.3 Greedy Cooperative Geographical Routing

In the previous sections, we investigated the optimum routing strategy in terms of the number of cooperating nodes and the transmission range per hop under a high node density regime. In this section, we use these results to design a *greedy geographical routing* algorithm suitable for sparse and medium density networks. In greedy geographical routing, packets are stamped with the positions of their destinations; all nodes know their own positions; and a node forwards a packet to its neighbor that is geographically closest to the destination, so long as that neighbor is closer to the destination [10]. Any geographical routing algorithm has two main components: information gathering and forwarding.

### 2.3.1 Information Gathering

In order for the geographical routing algorithm to work properly, the position information of the participating nodes should be available. We assume that a node determines its position by a positioning technique such as Global Positioning System (GPS). There is also a location service, which is used to determine the positions of the destination nodes. In order to forward the data from source to destination, the positions of the neighbor nodes also need to be determined. In typical implementations of geographical routing protocols, this information is gathered via periodic "HELLO" message broadcasts, where each node includes its id number and location in these messages. "HELLO" messages have a time-to-live (TTL) value equal to 1, which means that a receiving node does not re-broadcast the message. Note that in a network with vMISO links, the number of neighbors of each node is higher due to the increased transmission range of these links. In the previous section, we calculated the optimal transmission range in dense networks, i.e., $d_{n_{opt}} = n_{opt} g_{n_{opt}}(p_{opt})^{1/\beta} d_0(p_{opt})$. All nodes within this transmission range of a node are considered as the *vMISO neighbors* of the node. Thus, the information gathering component of typical geographical routing protocols should be extended to collect the position information from this extended neighbor set. Specifically, we assume that each node gathers $I$-hop neighbor information, where $I = \lceil d_{n_{opt}}/d_0(p_{opt}) \rceil$. This can be realized by setting TTL value to $I$.

### 2.3.2 Forwarding Algorithm

In order to conform to the optimal policy as much as possible, the *greedy* forwarding strategy should select a relay node that is $d_{n_{opt}}$ meters closer to the destination than the source itself. Furthermore, the selected relay node should also be able to conform to the optimal policy, i.e., it should have at least $n_{opt} - 1$ SISO neighbors[1] (i.e., node degree $n_{opt} - 1$). However, in general, there may not be such a node in the network satisfying both of these requirements. Therefore, the algorithm chooses the node that has at least $n_{opt} - 1$ SISO neighbors, and makes the most progress towards the destination. However, this strategy does not guarantee that the resulting path that is using vMISO transmissions is the minimum energy path. Thus, for each vMISO link, we check whether using a multi-hop SISO path is more energy efficient or not.

The details of the forwarding algorithm are as follows: Let node $v_1$ first determine the set of nodes $\mathcal{S}$ which are closer to the destination than itself and have at least a degree of $n_{opt} - 1$ by using the node position information collected at the information gathering step. Then, $v_1$ selects the node $v_2 \in \mathcal{S}$ that is the closest to the destination. Let the distance between $v_1$ and $v_2$ be $d_{12}$. If $d_{12} \leq d_{n_{opt}}$, and if the energy cost with direct vMISO transmission, $E^{vMISO}(k, d_{n_{opt}}, n_{opt})$, is less than the total energy cost of multi-hop SISO transmissions, $E^{SISO}(k, d_{12}) = K\, E^{SISO}(k, d_0)$, where $K$ is the number of SISO hops needed to reach $v_2$ from $v_1$, $v_1$ forwards data to $v_2$ by a direct vMISO transmission. If this is not the case, $v_1$ forwards the data to one of its SISO neighbors $v_3 \in \mathcal{S}$ that is the closest to the destination. Note that if $v_2$ is the destination node, the degree requirement is not considered.

In a greedy routing algorithm, if a node does not have a neighbor that is closer to the destination than the node itself, the packet is stuck at that node, and cannot be forwarded to another node. Thus, the greedy routing algorithm fails to find a path between the forwarding node and the destination. Since vMISO transmissions provide extended transmission ranges, this problem is solved to some extent. However, the degree constraint may still prevent finding a next hop node.

[1]We call those neighbors reachable by a direct SISO transmission, *SISO neighbors*.

### 2.3.3 Simulation Results

#### Effect of node density

In our simulation setup, we consider a 50m×50m square area, where the nodes are randomly distributed. The source and destination nodes lie at the opposite corners of this area. We perform the simulations for varying node densities, and our results represent the average of the measurements over 65 random topologies for each node density. The transmissions are attenuated by a random Rayleigh distributed amount, and a transmission is successfully received if the total received signal power is above a certain threshold determined by the required SER level. If a transmission is unsuccessful, it is repeated again over the same random fading channel. Let $d_{nom} = 10$m, $p_{nom} = 0.1$, $p = 0.05$, $\beta = 2$ and $n = 2$.

Investigating the effect of the node density of the network, we compare the results of the algorithms in which we allow vMISO and SISO, and MISO and SISO transmissions. In the algorithm that we allow MISO transmissions, all nodes are assumed to have $n$ antennas. Thus, in the forwarding phase of the algorithm, the constraint on the degree of the forwarding node and the next hop node is loosed when the transmission strategy is MISO.

In Figure 2.10, we depict the average total energy consumed per bit routed from the source to destination with vMISO, MISO and SISO systems. As expected, MISO energy consumption is the minimum and vMISO energy consumption is less than the energy consumption of SISO. Also note that the vMISO transmissions with optimal number of cooperating nodes, i.e., $n = 2$, performs better than the case when the number of cooperating nodes is higher, i.e., $n = 4$. Similarly, MISO transmissions with the optimal number of antennas, $n = 2$, overperforms the case when the number of antennas is more. Also, it is demonstrated that, MISO system consume less energy due to the missing local information exchange phase and the loosed constraint on the degree of the nodes on the path from the source to the destination.

In Figure 2.11, we depict the number of hops taken by the vMISO, MISO and SISO systems. The number of hops of a path is an important measure, since the paths with lower number of hops can provide higher end-to-end transmission rates.

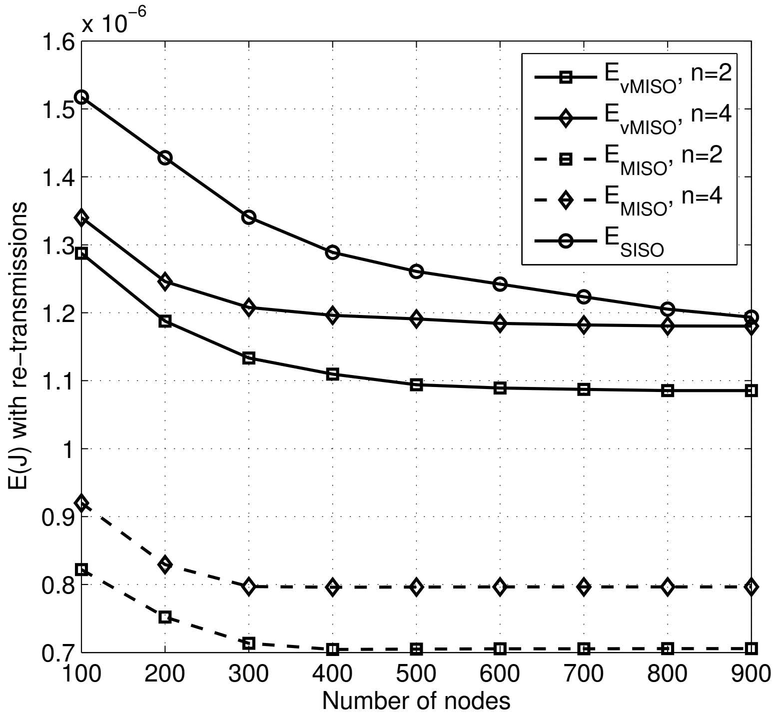


Figure 2.10: Energy per bit consumed with multi-hop vMISO, MISO and SISO systems.

The number of hops taken by the vMISO system with $n = 2$ is approximately half as many as the SISO system due to longer vMISO transmission range. When the number of nodes in the network increases, nodes can be found at ideal location between the source and destination, and thus, the number of hops with SISO decreases. However, we observe that vMISO with $n = 2$ and $n = 4$ cooperating nodes first decreases and then increases when the network gets denser. This is because, when there are few nodes in the network, even though cooperation is energy efficient, it cannot be used due to the degree constraint on the nodes. When network gets denser and the degree constraint on the nodes is less effective, cooperation is preferred, and the number of hops taken decreases due to long range vMISO transmissions. As the node density gets higher, such long range transmissions are no longer necessary to find a route, and thus, energy efficient shorter range transmissions are made.

Also, in Figure 2.11, it is observed that the number of hops taken with MISO is less than the vMISO system. This is due to the lack of degree constraint on the nodes and local information exchange phase in MISO systems, since we assumed

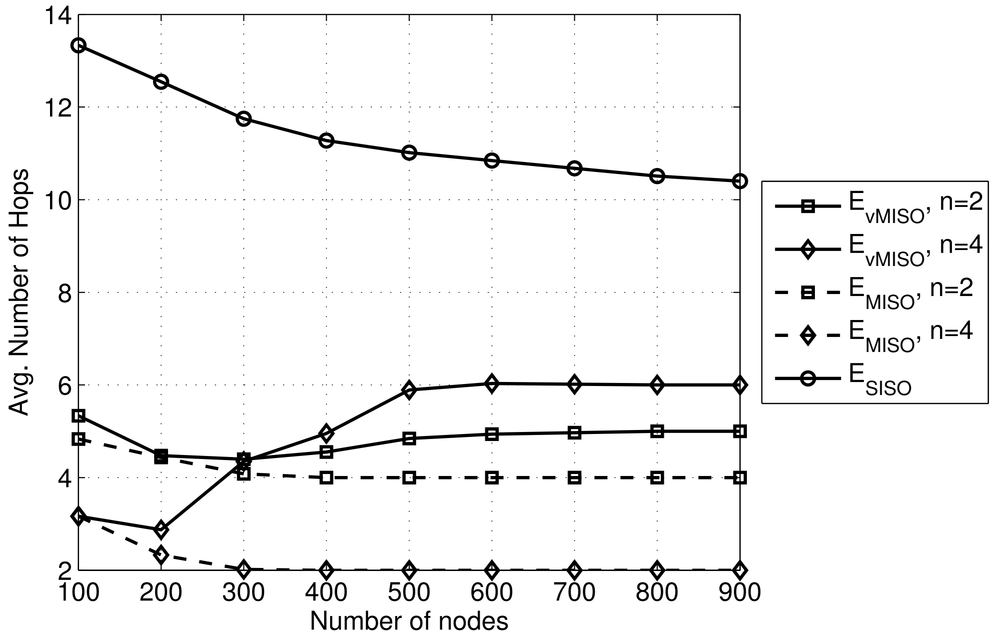


Figure 2.11: Number of hops with multi-hop vMISO and SISO systems.

there are $n$ co-located antennas in each node. Due to the same reasons, when the network gets denser, nodes can be found in ideal location, and thus, the number of hops taken with MISO decreases.

Finally, in Figure 2.12, we depict the percentage of trials in which a path between the source and the destination can be found using greedy geographical routing with respect to increasing network density. As demonstrated in the figure, using vMISO and MISO in sparse networks significantly helps in finding a path with greedy geographical routing. Note that vMISO performs slightly better finding route from source to destination. This is because of the degree constraint on the nodes in the forwarding algorithm in greedy geographical routing using vMISO, by which a node can be guaranteed to find a next hop node which is closer to destination than itself.

#### Effect of the distance between the source, $S$, and the destination, $T$, nodes

In our simulation setup, we consider a 100m×100m square area, where 700 nodes are randomly distributed. We perform the simulations for varying distances between the source and the destination nodes, and our results represent the average of the measurements over 60 random topologies for each node density. The unsuccessful transmissions are repeated if the transmission does not satisfy the required SER

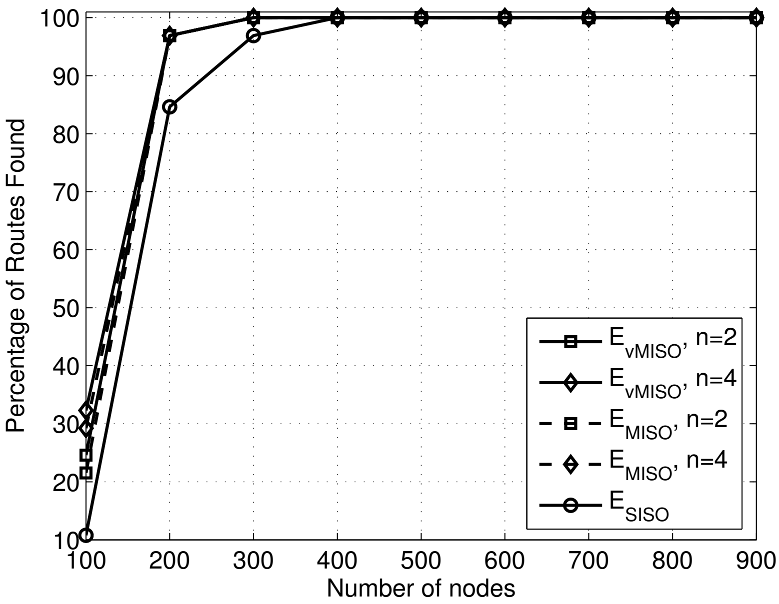


Figure 2.12: Percentage of trials in which a path found with multi-hop vMISO and SISO systems.

value as explained in the previous subsections. Let $d_{nom} = 10\text{m}$, $p_{nom} = 0.1$, $p = 0.05$ and $\beta = 2$.

In Figure 2.13, we depict the average total energy consumed per bit routed from the source to destination with vMISO and SISO systems. As expected, in each strategy energy consumption increases linearly when the distance between the source and the destination gets longer, and for longer distances vMISO performs much better than the lower distances. Also note that the vMISO transmissions with optimal number of cooperating nodes, i.e., $n = 2$, performs better than the case when the number of cooperating nodes is higher, i.e., $n = 4$, and SISO.

In Figure 2.14, we depict the number of hops taken by the vMISO and SISO systems. From this figure, it is observed that, the hops taken by SISO system increases linearly as the distance between source and the destination gets longer. The hops taken by vMISO systems increases with a smaller slope. Also note that, there is a zig-zag form for vMISO with $n = 4$. This is because, according to the distance to the destination, the algorithm chooses to use short range transmissions. When the distance is increased in the next step, it chooses to use long range transmission since it is energy efficient again.

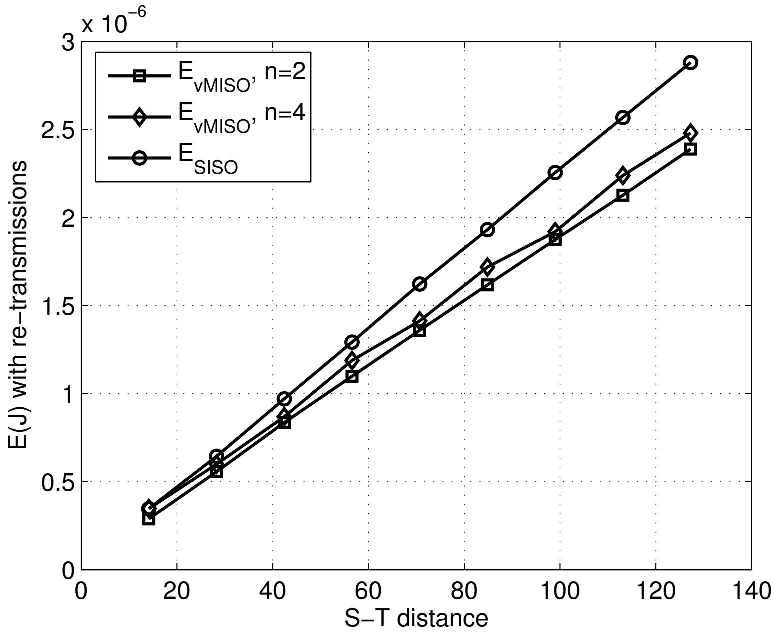


Figure 2.13: Energy per bit consumed with multi-hop vMISO and SISO systems.

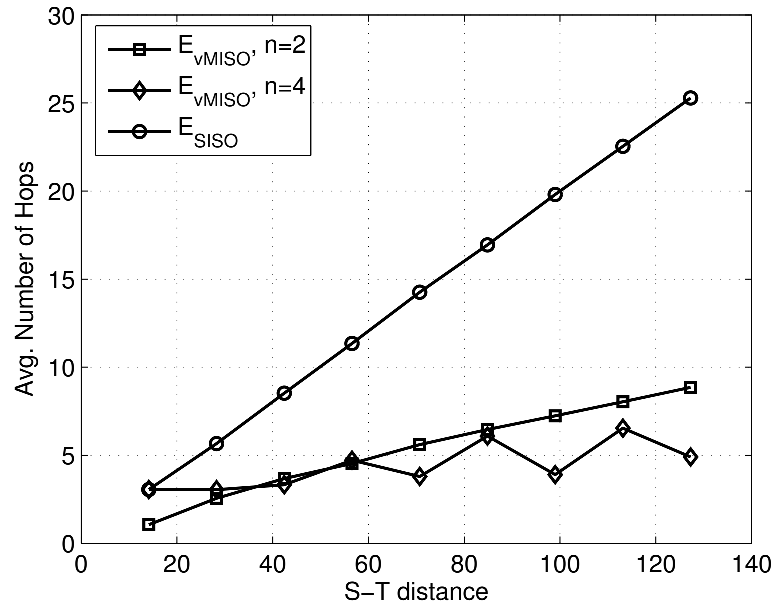


Figure 2.14: Number of hops with multi-hop vMISO and SISO systems.

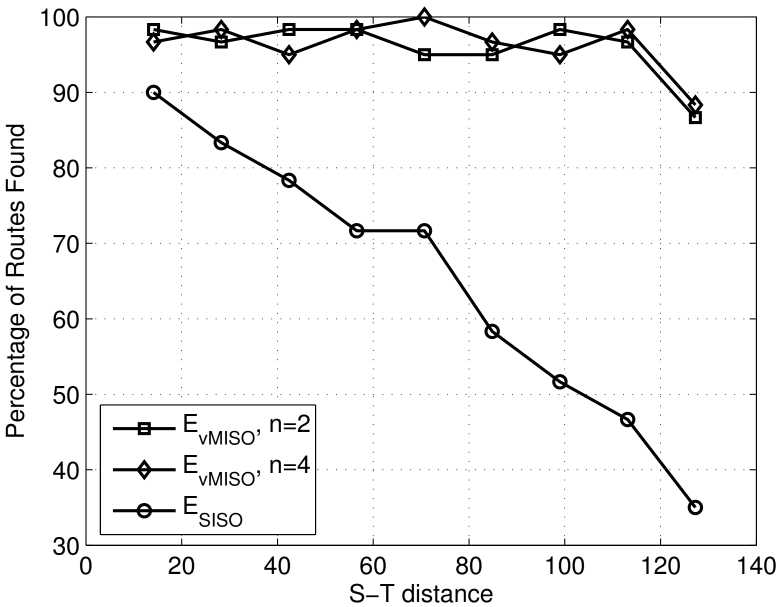


Figure 2.15: Percentage of trials in which a path found with multi-hop vMISO and SISO systems.

In Figure 2.15, we depict the percentage of trials in which a path between the source and the destination. As demonstrated in the figure, using vMISO when the network is sparse and the distance between the source and the destination nodes are very long helps in finding a path with greedy geographical routing. Note that with SISO transmissions, a critical decrease in the path finding performance is observed when the source-destination distance gets longer.

**Effect of $d_{nom}$**

In this simulation setup, we consider a 50m×50m square area, where 700 nodes are randomly distributed. We perform the simulations for varying target $d_{nom}$ values, and our results represent the average of the measurements over 60 random topologies for each node density. The unsuccessful transmissions are repeated if the transmission does not satisfy the required SER value as explained in the previous subsections.

Finally, Figure 2.16 is depicted when $p = 0.05$m, $p_{nom} = 0.1$ and $\beta = 2$. As expected, vMISO with $n = 2$ is the optimal strategy. Energy consumption decreases as $d_{nom}$ gets higher. This is because, when $d_{nom}$ gets higher vMISO and SISO

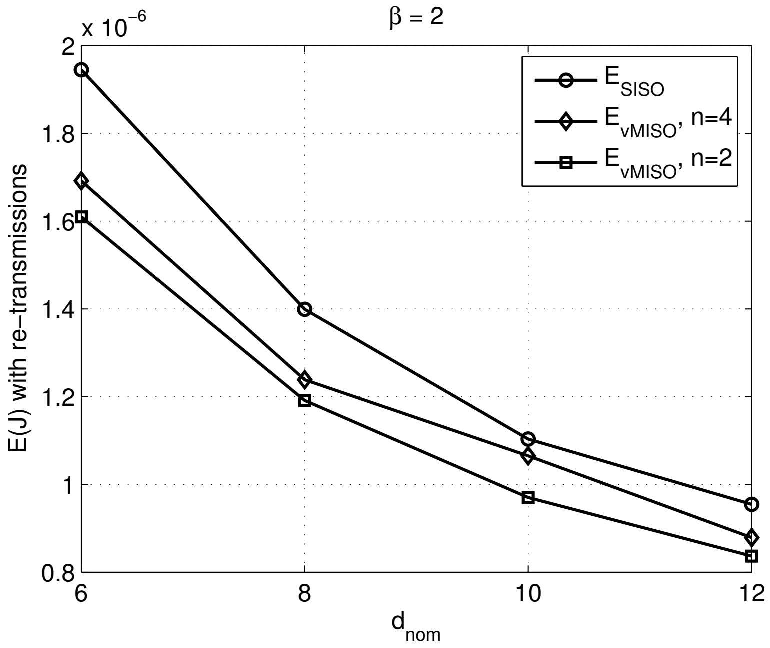


Figure 2.16: Energy per bit consumed with multi-hop vMISO and SISO systems.

ranges increase which leads to less number of hops needed to be taken to reach the destination node.

# Chapter 3

## NETWORK LIFETIME MAXIMIZATION WITH vMISO LINKS

In this chapter, our objective is to quantify the advantages of using vMISO transmissions in extending the network lifetime of energy-constrained wireless networks. Note that the main energy consumption in wireless networks is due to the radio circuitry. For example, in sensor networks the data collected by the sensors need to be transmitted to a remote central processor. If the central processor is located far from the sensors, the data is forwarded in a multi-hop fashion, i.e., sensor first transmits to a relay node, then from the relay node it is transmitted to the next relay node, and so on, until the data reaches its final destination (see Figure 3.1). In this case, in order to prolong the network lifetime, the node transmission powers and the path the data follows should be chosen judiciously.

We focus on energy efficient vMISO routing protocols, so our work appears similar in nature to the work by Chang and Tassiulas [2]. However, unlike previous studies, we consider the effects of channel fading on the quality of wireless reception, and we analyze the use of vMISO transmissions in mitigating those effects. Our focus in this chapter is on the "logical" problem of establishing paths that maximize the network lifetime using vMISO links, rather than on the development of practical protocols for full-fledged cooperative diversity implementation. One of our main contributions is the realistic channel and energy consumption model taking into account channel fading and transmitter-side cooperative diversity. Using the energy consumption model developed, we define the maximum lifetime routing problem with vMISO links. In addition, we design a novel energy efficient vMISO routing algorithm that calculates the best set of cooperating nodes between any two nodes and the best path between a source-sink pair maximizing the network lifetime,

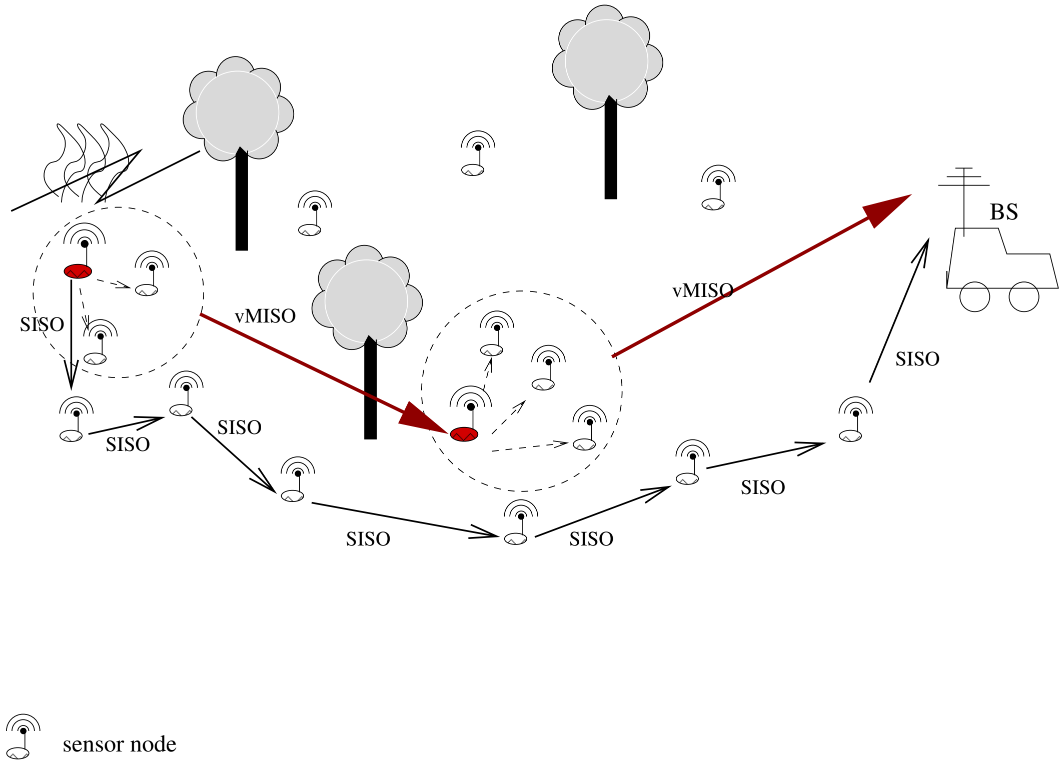


Figure 3.1: Routing with Cooperative Diversity.

and we present the comparison of network lifetime when vMISO routing algorithm is employed with the system where no cooperation is employed in clustered and uniformly distributed networks. Our results indicate that, on the average, more than two times increase in network lifetime is possible by employing vMISO links compared to the network lifetime using SISO links.

## 3.1 Background on Network Lifetime Prolongation in Wireless Networks

Most of the literature in this area has focused on routing techniques that extend the lifetime of a sensor or ad hoc network by taking into account the residual battery energy. In [27], Toh proposed the Conditional Max-Min Battery Capacity Routing (CMMBCR), which selects the shortest path for routing data from one node to the other in an ad hoc network such that all nodes on the path have remaining battery energy above a certain threshold. Singh et al. [28] presented an elaborate study of five different metrics, which are all a function of the node battery power and concluded that these metrics can give significant energy savings over naive hopcount-based metrics. In [29], Kar et al. proposed an online algorithm for routing messages in an ad hoc network, also based on the remaining battery energy of a node. Energy efficient routing techniques have also been proposed in several studies on sensor networks. Heinzelman et al. proposed a family of adaptive protocols called SPIN for energy efficient dissemination of information throughout the sensor network [30]. In [7], Heinzelman et al. proposed LEACH, a scalable adaptive clustering protocol in which nodes are organized into clusters and system lifetime is extended by randomly choosing the cluster-heads. Lindsey, et al. proposed an alternative data gathering scheme called PEGASIS in [40], in which nodes organize themselves in chains, also with rotating elections, for communicating data. Lindsey, et al [41] studied different data gathering schemes and explored the trade-off between energy consumed and delay incurred.

The problem of maximizing data collection can also be formulated as a multi-commodity flow problem. There is a vast literature on algorithms for multi-commodity flow problems and their application to networking. In [2], Chang and Tassiulas use the multi-commodity flow formulation for maximizing the lifetime of an ad hoc network. The authors proposed a class of flow augmentation and flow redirection algorithms that balance the energy consumption rates across nodes based on the remaining battery energy of these nodes. This approach is shown to significantly increase the network lifetime. Zussman and Segall extended this work by also considering the limitation on bandwidth resources jointly [37]. In [21], the authors considered the routing problem in MANET with the goal of maximizing the lifetime of the network. Their approach is also based on the formulation of multi-commodity flow, and they proposed a distributed routing algorithm that reaches the optimal solution to within an asymptotically small relative error. Bhardwaj and Chandrakasan [38] examined feasible role assignments (FRA) of nodes as a means of maximizing the lifetime of aggregating as well as non-aggregating sensor networks, and also made use of linear programs based on network flows. Kalpakis et al. examined the MLDA (Maximum Lifetime Data Aggregation) and the MLDR (Maximum Lifetime Data Routing) problems in [39], again by formulating those problems as an LP using multi-commodity network flows. The authors observed that as the network size increases, solving the LP takes considerable time and proposed some clustering heuristics to achieve near-optimal performance. As the size of the LP increases, it becomes desirable to solve this problem approximately but quickly. In [36], Ordonez and Krishnamachari developed optimization models to study the lifetime maximization problem in sensor networks. In this work, the authors showed that maximizing the total information extraction subject to energy constraints is equivalent to minimizing energy usage subject to information constraints. They also showed by numerical examples how the optimal solution varies with energy and fairness constraints.

## 3.2 Channel Model

Channel model in this chapter is the same as the channel model in the previous chapter. Thus, signals are modulated by BPSK and the receiver has full CSI. We consider a wireless channel with Rayleigh flat fading channels with AWGN with zero mean and one-sided spectral density, $N_0$.

In the following sections, we calculate the required minimum transmission power in a flat-fading channel with SISO, MISO and vMISO systems for a given target average SNR. For each of these systems, a minimum average SNR requirement has to be satisfied for a given target average SER, $p$. The relative difference in the transmission powers SISO and vMISO systems are going to be used in the forthcoming section to quantify the energy consumption in the respective systems.

### 3.2.1 SISO system

In a SISO system such as the one depicted in Figure 3.2, there is a single transmitting antenna and a single receiving antenna. Let $s_0(t)$ be the complex envelope of the modulated signal transmitted during the symbol interval $0 \leq t \leq T_s$. Then, the symbol received at a node at an Euclidean distance $d_0$ to the transmitter is defined by:

$$r_0(t) = \alpha_0 e^{j\phi} d_0^{-\beta/2} s_0(t) + w_0(t),$$

where $\alpha_0$ is the random attenuation due to fading with Rayleigh distribution, $w_0(t)$ is the additive channel noise and $\beta$ is the path loss coefficient which is usually between 2 and 4. With the fading assumed to be slowly varying relative to the

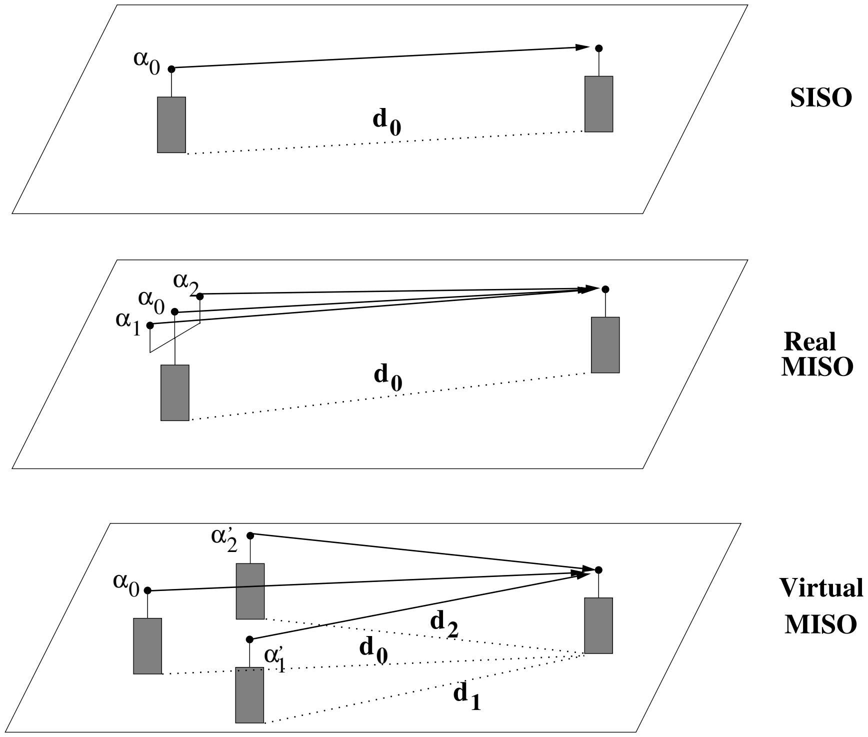


Figure 3.2: SISO, real MISO and virtual MISO systems.

symbol duration $T_s$, we should be able to estimate and remove the unknown phase shift $\phi$. Thus, the average SNR at the output of the receiver $SNR_0$, is:

$$\begin{aligned} SNR^{\mathrm{SISO}} &= \frac{E\left\{|s_0(t)|^2 d_0^{-\beta}\right\}}{E\left\{|w_0(t)|^2\right\}}\mathbf{E}\left[\alpha_0^2\right], \\ &= \frac{e}{N_0}\mathbf{E}\left[\alpha_0^2\right] d_0^{-\beta}, \end{aligned} \tag{3.1}$$

where $e$ is the symbol energy and $N_0$ is the one-sided noise spectral density.

For a target $SNR \geq \gamma$, the minimum energy per symbol is

$$e^{\mathrm{SISO}} = \frac{\gamma N_0}{\mathbf{E}\left[\alpha_0^2\right]} d_0^{\beta}. \tag{3.2}$$

### 3.2.2 Real MISO Systems

In real MISO systems all antenna elements are located at the same location and transmit with the same power (see Figure 3.2). Then, it follows from our discussion for SISO systems and from Eq. (1.5) that the average SNR of the received signal at a distance $d_0$ when $N$ co-located antenna elements transmit using the systematic high rate complex orthogonal space-time block codes is:

$$SNR^{\mathrm{MISO}} = \frac{e}{N_0}\mathbf{E}\left[\sum_{i=0}^{N-1}\alpha_i^2\right] d_0^{-\beta}. \tag{3.3}$$

If for each antenna element the fading coefficients $\alpha_i$ are characterized by independent and identically distributed Rayleigh random variables, $\alpha$, then for all $i$, $\alpha_i^2$ is exponentially distributed with the same parameter. Also, it has been demonstrated by Monte Carlo simulations that, for the same target SER value, the target average SNR for MISO systems is smaller than the target SNR of SISO systems [6]. The ratio between two SNR values is referred as diversity gain. Let $\tau_N$ be the diversity gain provided by a MISO system with $N$ antennas. Thus, while the target SNR required for SISO system is $\gamma$, the target SNR required for MISO systems with $N$ antennas is $\gamma/\tau_N$, and minimum symbol energy required for a MISO transmission is,

$$e^{\text{MISO}} = \frac{\gamma}{\tau_N} \frac{N_0}{N\mathbf{E}\left[\alpha^2\right]} d_0^{\beta}. \tag{3.4}$$

By comparing Eqs (3.2) and (3.4) one can see that a MISO system with $N$ transmitters can achieve $N\tau_N$ fold increase in average SNR (diversity gain of $N_t$) over SISO system, when energy per symbol is the same in both cases. Thus, SISO and MISO systems can provide the same SER when each antenna element transmits with $\frac{1}{N\tau_N}$th power of SISO transmission.

### 3.2.3 Virtual MISO systems

In the previous calculations we could have omitted the signal attenuation due to path loss, since all antenna elements are located at the same location and relative effect of path loss on each antenna elements would be the same. However, in vMISO systems, the distances between the cooperating nodes and the receiver node may vary according to the locations of the nodes. The cooperating nodes should transmit with the same power, so that the receiver can combine the received signals by linear processing and thus reducing the complexity of receiver circuitry. Therefore, for vMISO systems, the average SNR formula given for MISO system is updated as:

$$SNR^{\text{vMISO}} = \frac{e}{N_0} \mathbf{E}\left[\sum_{i=0}^{N-1} \alpha_i^2 d_i^{-\beta}\right], \tag{3.5}$$

where $d_i$ is the distance between node $i$ and the receiver. For independent and identically distributed fading coefficients $\alpha_i = \alpha$, $i = 0, 1, \ldots, N$ and for a target $SNR \geq \gamma/\tau_N$, which is provided by the diversity gain, the minimum symbol energy

Table 3.1: Diversity Gain and Code Rate for $2 \leq N \leq 4$ Transmit Antennas When $p = 0.005$ [6]

| $N$ | Diversity Gain (dB) | $\tau_N$ | STBC Code Rate |
|---|---|---|---|
| 2 | 6.5 | 4.4668 | 1 |
| 3 | 10.3 | 10.7406 | 1/2 |
| 4 | 11.3 | 13.5216 | 1/2 |

is

$$e^{\text{vMISO}} = \frac{\gamma}{\tau_N} \frac{N_0}{\mathbf{E}\left[\alpha^2\right] \sum_{i=0}^{N-1} d_i^{-\beta}}. \tag{3.6}$$

Table 3.1 shows the diversity gain for $N = 2, 3, 4$ when $p = 0.005$ with suitable STBC transmission blocks.

## 3.3 Network Lifetime Maximization with vMISO Routing

In this section, we consider a realistic abstract model developed according to the discussions in the previous sections. Using this abstract model, we develop the optimal network lifetime maximization problem with vMISO routing. Our focus in this paper is on the "logical" problem of establishing paths that maximize the network lifetime, rather than on the development of practical protocols for full-fledged cooperative diversity implementation. Thus, we do not address medium-access issues or the constraints of time synchronization. We refer the interested readers to [6] for the physical layer discussion of cooperative diversity systems, and to [50] for time synchronization issues. In addition, we assume that nodes are synchronized such that a node is awake only when either it is scheduled to send/receive a packet to/from one of its neighbors. This can be achieved using time division multiple access (TDMA). The duty cycle of the node depends on the rate at which it transmits and receives information. Under these assumptions, there is no power consumed by idle listening.

There are many definitions of network lifetime in the literature. In this work, we adopt an extensively used definition first presented by Chang and Tassiulas [2]: The network lifetime is defined as the time when the first node in the network depletes all of its battery energy.

The system operates as follows: When node $i$ decides to transmit to node $j$, it first determines a set of cooperating nodes in its neighborhood [1]. Once a set of nodes is selected, the source node $i$ transmits the original data destined to node $j$ sequentially to each of the cooperating nodes in the set. During this process, node $i$ may forward to each cooperating node the appropriately coded data according to the generalized complex space-time block codes [22] or leave the task of encoding to the cooperating node [2]. We assume that the receiver has the exact channel information which may be gathered by the transmission of initial pilot tones from the cooperating nodes a priori to data transmission. Once the aforementioned initial setup is completed, the source and cooperating nodes simultaneously transmit to the receiver node.

## 3.4 Network Model

The network is modeled by a directed graph $G(N, A)$ where $N$ is the set of nodes, $A$ is the set of directed edges $(i, j)$ where $i, j \in N$. We assume that there is no limit on the maximum transmission power, so that all nodes in $N$ can communicate with each other as long as they have sufficient energies. First, assume that there is a single flow generated at rate $Q_s$ in the network at source node $s$ with destination node $t$. Let $q_{ij}$ be the *aggregate* flow rate from node $i$ to node $j$. Each node $i$ can cooperate with the nodes in its neighborhood $\mathcal{N}(i)$, where $\mathcal{N}(i)$ is defined as the set of nodes lying in a circular area with radius $r$ and its center located at the position of node $i$. Each node $i$ may cooperate with a different set of nodes $\mathbf{v}_{ij} = (i, v^1, v^2, \ldots, v^m)$, $v^m \in \mathcal{N}(i)$, $m \leq |\mathcal{N}(i)|$ while transmitting to node $j$. Let $\mathbf{V}_{ij} = \{\mathbf{v}_{ij}^1, \mathbf{v}_{ij}^2, \ldots, \mathbf{v}_{ij}^{M_{ij}}\}$ be the set of vectors of different cooperating sets used by node $i$ while transmitting to node $j$. Note that the cardinality of this set, $|\mathbf{V}_{ij}| = M_{ij}$, is equal to $2^{|\mathcal{N}(i)|-1}$, since it contains all subsets of $\mathcal{N}(i)$ containing node $i$. Define the flow rate from node $i$ to node $j$ sent using the cooperating set $\mathbf{v}_{ij}^c$, as $q_{ij}^{(c)}$. Note that $\sum_{c=1}^{M_{ij}} q_{ij}^{(c)} = q_{ij}$.

[1] The definition of neighborhood of a node and how to select nodes in a neighborhood will become clear in a while.

[2] In this work, we omit the energy consumption due to processing, so either method can be selected.

## 3.5 Energy Consumption Model

Let $E_i$ be the initial energy of node $i$ and $d_{ij}$ be the euclidean distance between node $i$ and $j$. Also, let $\hat{e}_{ij}$ be the energy required to transmit one bit from node $i$ to node $j$ when SISO transmission is employed. In order to satisfy an average SNR requirement, i.e., $SNR > \gamma$, the energy in a bit should be at least

$$\hat{e}_{ij} = \frac{\gamma N_0}{E[\alpha^2] d_{ij}^{-\beta}}, \tag{3.7}$$

where $N_0$ is the additive noise power and $E[\alpha^2]$ is the second moment of the Rayleigh fading. If vMIMO transmission is employed, as discussed in the previous sections, the transmission power of the source (as well as a cooperating) node is reduced by a factor which depends on the set of cooperating nodes and the diversity gain. Let us define the ratio of minimum transmission powers used to satisfy an SNR requirement in vMISO and in SISO systems as $R_{ij}^c$, where $c$ represents the index of the cooperation set $\mathbf{v}_{ij}^c \in \mathbf{V}_{ij}$ used in vMISO case. In order to satisfy the average SNR requirement, $\gamma/\tau_{|\mathbf{v}_{ij}^c|}$, where $\tau_{|\mathbf{v}_{ij}^c|}$ is the diversity gain provided by the cooperation set $\mathbf{v}_{ij}^c$, each vMISO cooperating node should transmit with at least

$$R_{ij}^c = \tau_{|\mathbf{v}_{ij}^c|} \left[ 1 + \frac{\sum_{k \in \mathbf{v}_{ij}^c} d_{kj}^{-\beta}}{d_{ij}^{-\beta}} \right] \tag{3.8}$$

times less power than the power required for a SISO transmission.

Recall that the systematic complex orthogonal space time block codes usually have code rates less than 1. In other words, in order to transmit $l$ different symbols $l_{|\mathbf{v}_{ij}^c|}$ consecutive transmissions have to be made by each antenna element. Let us define $\xi(|\mathbf{v}_{ij}^c|) = l/l_{|\mathbf{v}_{ij}^c|}$ as the code rate of the space time block code used with $|\mathbf{v}_{ij}^c|$ antenna elements. In this work, we use the code rates given for systematic complex orthogonal space-time block codes summarized in Table 1.1.

Now, we are ready to determine the energy consumed per bit of information sent by the source node $i$ to node $j$ in vMISO case, $e_{ij}$. First consider the energy consumed per $l$ bits of information sent:

$$l \cdot e_{ij}^c = \sum_{k \in \mathbf{v}_{ij}^c} l \left( \hat{e}_{ik} + e_t \right) + l_{|\mathbf{v}_{ij}^c|} \left( \frac{\hat{e}_{ij}}{R_{ij}^c} + e_t \right) \tag{3.9}$$

The first term in (3.9) represents the energy consumption due to the initial transmission of the $l$ bits of information to each of the nodes in the cooperation set $\mathbf{v}_{ij}^c$ of node $i$, where $e_t$ is the energy consumed due to transmission circuitry. The second term represents the energy consumption due to the cooperative transmission of the data to the destination node $j$. Note that when node $i$ transmits data to node $j$ it transmits with power that is $R_{ij}^c$ times less than the transmission power with SISO transmission. Also, note that the source node makes $l_{|\mathbf{v}_{ij}^c|}$ number of consecutive transmissions in order to relay $l$ bits of information.

The energy consumed per bit of information sent by the source is determined by dividing both sides of Eq(3.9) by $l$.

$$e_{ij}^c = \sum_{k \in \mathbf{v}_{ij}^c} (\hat{e}_{ik} + e_t) + \frac{1}{\xi(|\mathbf{v}_{ij}^c|)} \left( \frac{\hat{e}_{ij}}{R_{ij}^c} + e_t \right) \tag{3.10}$$

In the above calculation, we assumed that BPSK modulation is used. If other modulation techniques such as QPSK, QAM were used the same derivation is applicable when calculating the energy consumed per symbol.

The energy consumed per bit of information received by the a node $j$ is a constant $e_r$.

Let node $h$ be a node in the cooperation set, $\mathbf{v}_{ij}^c$, of the source node $i$. The energy consumed by node $h$ while assisting node $i$ for transmission of a bit of information to node $j$ is determined as:

$$\tilde{e}_{ij}^c = e_r + \left( \frac{\hat{e}_{ij}}{R_{ij}^c} + e_t \right) \frac{1}{\xi(|\mathbf{v}_{ij}^c|)}. \tag{3.11}$$

First term in Eq (3.11) is due to the energy consumption per bit of information received from the source node $i$, and the second term is due to the energy consumption per bit of information cooperatively transmitted to node $j$. Note that this result follows from the fact that for all nodes $h \in \mathbf{v}_{ij}^c$ the transmission power should be the same in order to correctly decode the generalized space-time codes.

Finally, let the energy consumed by the destination node $j$ be $\breve{e}_{ij}^c$. To receive $l$ bits of information, destination node receives $l_{|\mathbf{v}_{ij}^c|}$ bits of information. Therefore, energy consumed by receiving one bit of information is calculated by the following:

$$\breve{e}_{ij}^c = e_r \frac{1}{\xi(|\mathbf{v}_{ij}^c|)}. \tag{3.12}$$

Given a routing strategy which results in the flow vectors $q_{ij}^{(c)}$, the aggregate energy consumption by node $i$ if it is acting as a source node, cooperating node or receiving node is given respectively as:

$$e_i^{source} = \sum_{j \in N} \sum_{c=1}^{M_{ij}} q_{ij}^{(c)} e_{ij}^{c} \tag{3.13}$$

$$e_i^{coop} = \sum_{j \in N} \sum_{(c,k): i \in \mathbf{v}_{kj}^{c}} q_{kj}^{(c)} \tilde{e}_{kj}^{c} \tag{3.14}$$

$$e_i^{receive} = \sum_{j \in N} \sum_{c=1}^{M_{ij}} q_{ij}^{(c)} \breve{e}_{ij}^{c} \tag{3.15}$$

## 3.6 System Lifetime Optimization Problem

The lifetime of node $i$ under a given flow vector $\mathbf{q}$=$\{q_{ij}^{(c)}\}$ and corresponding cooperation set $\mathbf{v}_{ij}^{c}$ is given by,

$$T_i(\mathbf{q}) = \frac{E_i}{e_i^{source} + e_i^{coop} + e_i^{receive}} \tag{3.16}$$

We define system lifetime as the duration of time until the first node drains out its battery. Hence, the minimum lifetime over all nodes gives the system lifetime, i.e.,

$$T_{sys}(\mathbf{q}) = \min_{i \in N} T_i(\mathbf{q}) \tag{3.17}$$

We aim to find the flow that maximizes the system lifetime under flow conservation condition, i.e.,

$$\sum_{i \in N, i \neq j} \sum_{c=1}^{M_{ij}} q_{ij}^{(c)} = \sum_{k \in N, k \neq j} \sum_{c=1}^{M_{jk}} q_{jk}^{(c)}. \tag{3.18}$$

Eq.(3.18) ensures that total flow routed between nodes is conserved. Note that we do not need to write down flow conservation equation for the cooperating nodes, $m \in V_{ij}$, since the flow incoming from the source node $i$ is directly sent to node $j$, i.e., there is no splitting (routing) of such a flow at node $m$ (see Figure 3.3).

Given the source and destination nodes and the information generation rate at the source node, the problem of maximizing system lifetime $T$ is equivalent to the following nonlinear optimization problem:

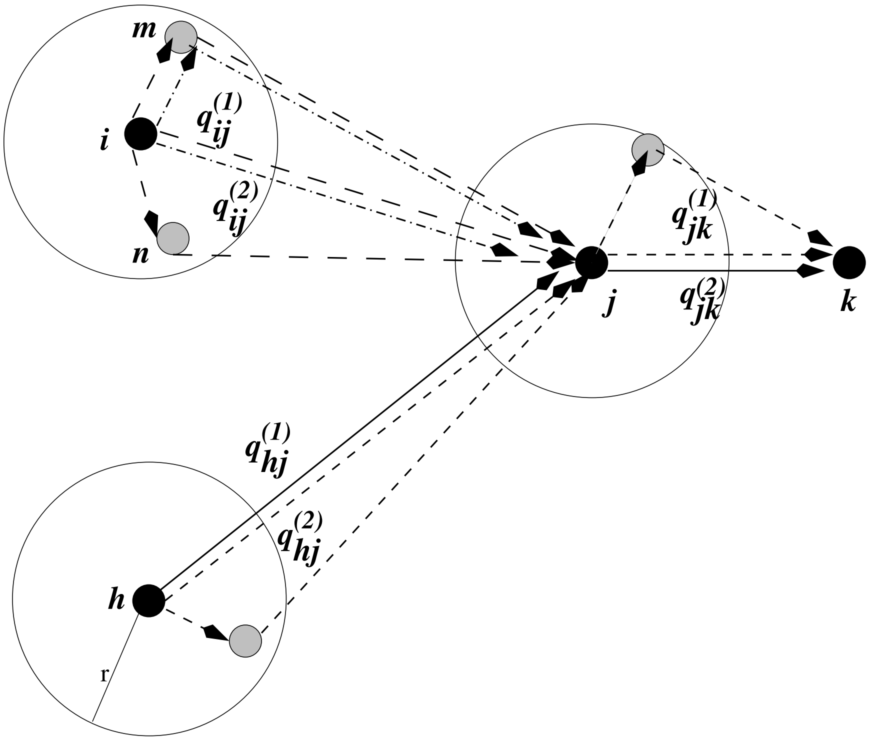


Figure 3.3: Flow conservation condition at node $j$

$$\max T \tag{3.19}$$

$$\sum_{j\in N}\left[\sum_{c=1}^{M_{ij}} e_{ij}^{c}\hat{q}_{ij}^{(c)} + \sum_{(c,k):i\in \mathbf{v}_{kj}^{c}} \tilde{e}_{kj}^{c}\hat{q}_{kj}^{(c)} + \sum_{c=1}^{M_{ij}} \breve{e}_{ij}^{c}\hat{q}_{ij}^{(c)}\right] \leq E_i,\ \forall i \in N \tag{3.20}$$

$$\sum_{i\in N, i\neq j}\sum_{c=1}^{M_{ij}} \hat{q}_{ij}^{(c)} = \sum_{k\in N, k\neq j}\sum_{c=1}^{M_{jk}} \hat{q}_{jk}^{(c)},\ \forall j \in N - s, t \tag{3.21}$$

$$\hat{q}_{ij}^{(c)} \geq 0,\ \forall i \in N \tag{3.22}$$

where $\hat{q}_{ij}^{(c)} = Tq_{ij}^{(c)}$ is the amount of flow transmitted from node $i$ to node $j$ using the cooperating set $\mathbf{v}_{kj}^{c}$ in $T$ time units.

Unlike the system maximization problem presented in [2], the above optimization problem is not a linear program, since $\tilde{e}_{ij}^{c}$ depends on the choice of the cooperation set $\mathbf{v}_{ij}^{c}$ in a nonlinear fashion. This makes the optimization problem harder to solve and motivates us to investigate heuristic solutions one of which is discussed in the next section.

## 3.7 Energy Efficient vMISO Routing Algorithm

Our energy efficient routing algorithm belongs to a class of flow augmentation algorithms. In this algorithm, at each iteration the following two steps are followed:

1. For each node pair $(i, j)$, $i, j \in N$ the best cooperation set, $\mathbf{v}_{ij}^c \in \mathbf{V}_{ij}$, is selected. This choice of cooperation sets results in a modified graph $G'(N, A')$, where the edges $(i, j) \in A'$ correspond to the cooperative transmission from the set of nodes $\mathbf{v}_{ij}^c$ to node $j$.

2. In the modified graph, assign a cost to each edge in $A'$. Calculate the shortest cost paths from the origin nodes to the destination nodes using the vMISO links.

At each iteration, the flow is augmented by an amount of $\lambda Q_s$ on the shortest cost path, where $\lambda$ is the augmentation step size. After the flow augmentation, the shortest cost paths are recalculated and the procedures are repeated until any node $i \in N$ runs out of its initial total energy $E_i$. As a result of the algorithm, we obtain the flow which will be used at each node to properly split the incoming traffic.

### 3.7.1 Selection of Cooperation Set

In order to determine the best cooperation set $\mathbf{v}_{ij}^c$, we need to select a cost function quantifying the relative energy costs of different choices of cooperation sets. There are two parameters to consider in calculating the relative energy cost $\rho_{ij}^c$. One is the energy expenditure per bit of data flowing from the set $\mathbf{v}_{ij}^c$ to node $j$, and second is the minimum of the initial energies of the nodes in $\mathbf{v}_{ij}^c$ and the energy of the receiver node $j$. A good candidate for the cooperation set should consume low energy, and should avoid nodes with small available energy since we would like to maximize the minimum lifetime of all nodes. Therefore, the cost function should be such that when the nodes have plenty of energy, the energy expenditure term is emphasized, while if the energy of a node becomes small the residual energy term should be more emphasized. Thus, for a particular cooperation set $\mathbf{v}_{ij}^c$ used to transmit data from node $i$ to node $j$, we consider the following cost function, $\rho_{ij}^c$:

$$\rho_{ij}^c = \frac{e_{ij}^c + \sum_{k \in \mathbf{v}_{ij}^c} \tilde{e}_{ij}^c}{\min_{k \in \mathbf{v}_{ij}^c}[E_k]} \cdot \frac{\breve{e}_{ij}^c}{E_j}, \tag{3.23}$$

where $e_{ij}^c$, $\tilde{e}_{ij}^c$ and $\breve{e}_{ij}^c$ are defined in Eqs. (3.10), (3.11) and (3.12) respectively. Note that the numerator in the first part of Eq (3.23) represents the total consumption of energy for transmission of a bit of data using nodes $\mathbf{v}_{ij}^c$ to node $j$, and the denominator represents the minimum available energy of the nodes in $\mathbf{v}_{ij}^c$. In the second part, the numerator represents the total consumption of the receiver node, while the denominator represents the available energy of the receiver node. This second term is needed to make sure that we take into account the effect of the code rate of the chosen STBC transmission block to the energy consumption of the receiver node, $j$. The best cooperation set $\mathbf{v}_{ij}^{c^*}$ is thus selected from $\mathbf{V}_{ij}$, as

$$c^* = \text{argmin}_{c=1,\ldots,M_{ij}} \rho_{ij}^c.$$

### 3.7.2 Routing Algorithm

Once the best cooperation set for each pair of nodes in the network is selected, the origin node $s$ calculates the shortest cost path to its destination node $t$. Our objective is to find the best link cost function which leads to the maximization of the system lifetime. A good link cost function should have the same characteristics as the relative cost function considered in the selection of the cooperation set. In particular, when all nodes have plenty of energy, the minimum total consumed energy path is better off, whereas towards the end avoiding the small residual energy node becomes more important. Thus, we use the cost function $\rho_{ij}^{c^*}$ as the link cost $l_{ij}$ for the link between node $i$ and $j$.

The path cost is computed by the summation of the link costs on the path, and the algorithm can be implemented with any existing shortest path algorithms including the distributed Bellman-Ford algorithm [51].

## 3.8 Numerical Results

In this section, we attempt to characterize the effects of different distributions of nodes in the network on network lifetime. In our simulations, we compare the lifetime of the networks employing vMISO links according to the algorithm given in Section 3.7 with the networks where SISO links are employed. When SISO links are employed, we again employ a flow-augmentation based routing algorithm similar to

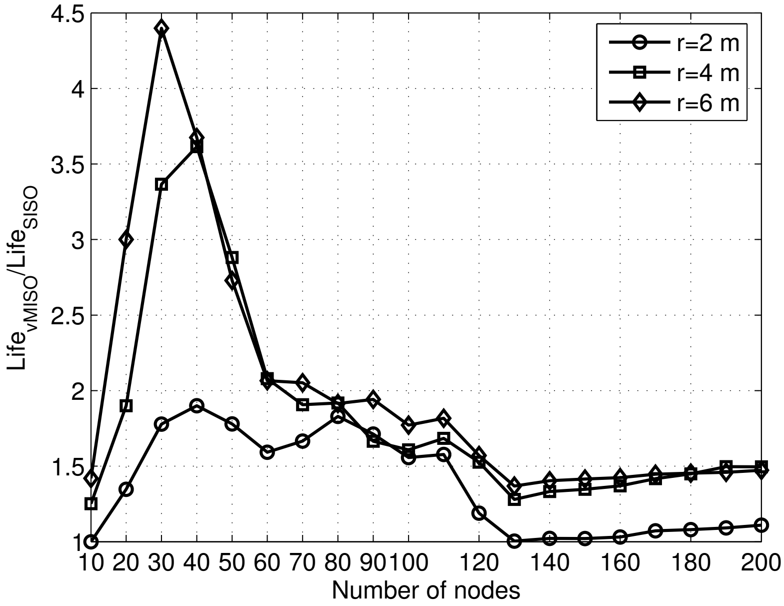


Figure 3.4: Effect of node density on network lifetime when the source and the destination nodes are placed at the opposite corners of the area.

the one described in Section 3.7. However, this time, we use a cost function

$$c_{ij} = \frac{\hat{e}_{ij}}{E_i}\frac{e_r}{E_j}, \tag{3.24}$$

where $\hat{e}_{ij}$ is defined as in Eq.(3.7), $e_r$ is the energy consumption due to the receiver circuitry and $E_i$ and $E_j$ are the residual energies of node $i$ and $j$, respectively.

In the simulations, we assume a simplified energy model given in [2], where $\hat{e}_{ij} = \epsilon_{amp} d_{ij}^{\beta}$. The transmissions are attenuated by a Rayleigh distributed amount, and a transmission is successively received if the total received signal power is above a certain threshold determined by the required SER level. If a transmission is unsuccessful, it is repeated again over the same random fading channel. We use the following values in the simulations: $\epsilon_{amp} = 100pJ/bit/m^{-\beta}$, $e_r = 50nJ/bit$, $\lambda = 1$, and $\beta = 2$. Assuming there is a flow at each second, we set the cooperation set and link cost updating period as 10 seconds.

In the first experiment, we investigate the change in network lifetime with respect to node density. In this experiment, nodes are uniformly distributed in an area of 100 m by 100 m. Our results in Figure 3.4 and Figure 3.5 represent the average of 50 instances of randomly network topologies, when the neighborhood radius is $r = 2, 4, 6$ meters. Although there is no limitation on transmission energies, the neighborhood radius is important since cooperation sets are constructed from the nodes in the neighborhood of a source node.

For Figure 3.4 and Figure 3.5, we placed one source and one destination at the opposite corners of the area and set their initial energies to the three times the initial energies of the other nodes in the network to be able to see the effect of the density to the lifetime of the network without letting the source and the destination nodes to deplete their batteries before the other nodes in the network. In Figure 3.4, it is demonstrated that, first, the ratio of thethe network lifetime with vMISO transmissions increases more than the network lifetime with SISO transmissions as the number of nodes in the network increases, and then, the network lifetime with vMISO transmissions approaches to the network lifetime with SISO transmissions. This result is expected, since as the number of nodes in the network increases, the number of nodes that a node can cooperate to establish a vMISO link also increases. As the number of nodes in the network continues to grow, nodes can be found at ideal location between the source and the destination. For this reason, as the node density gets higher, energy efficient SISO transmissions are preferred to the vMISO transmissions on some of the links of the routing path. The critical point, when $r$ is 6 m, where the network lifetime with vMISO links is more than 4 times the network lifetime with SISO links is observed when the number of nodes is 30. In Figure 3.5, it is demonstrated that lifetime with vMISO links increases with a higher slope than the lifetime with SISO links when the number of nodes is smaller than 40. And the difference reaches to the top when number of nodes is 30. Furthermore, in Figure 3.4, when the neighborhood radius (cooperation set radius), $r$, is increased, we observe an increase in the ratio of the lifetime with vMISO transmissions to the lifetime with SISO transmissions. This is due to the fact that, since nodes are uniformly distributed, as $r$ is increasing, the number of nodes that are in the cooperation range of a node increases. This provides a node the chance of choosing better cooperation sets for vMISO transmissions, which explains the increase in the lifetime with vMISO transmissions.

To have a better observation on the effect of the node density to the network lifetime, we assumed, each flow is transmitted from a randomly chosen source node to a randomly chosen destination node, instead of placing the source and the desti-

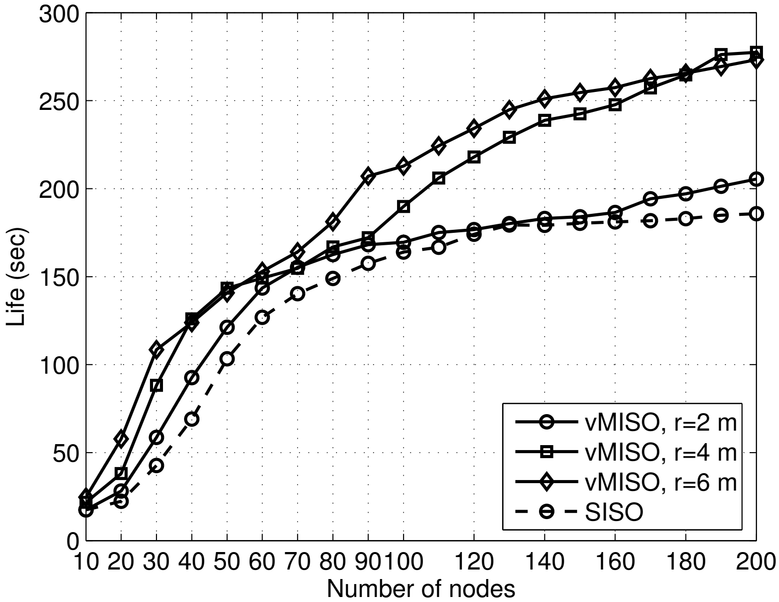


Figure 3.5: network lifetime with vMISO and SISO links when the source and the destination nodes are placed at the opposite corners of the area.

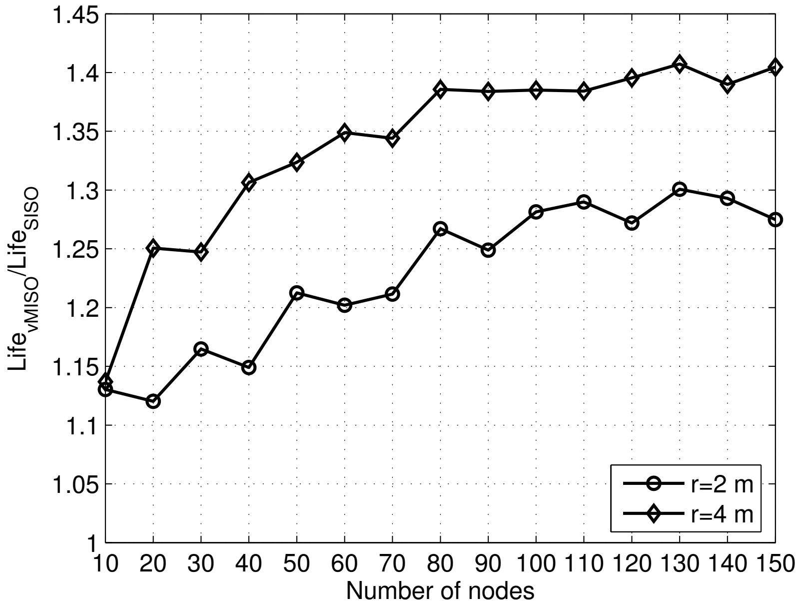


Figure 3.6: Effect of node density on network lifetime when the source and the destination nodes are randomly placed for each flow transmission.

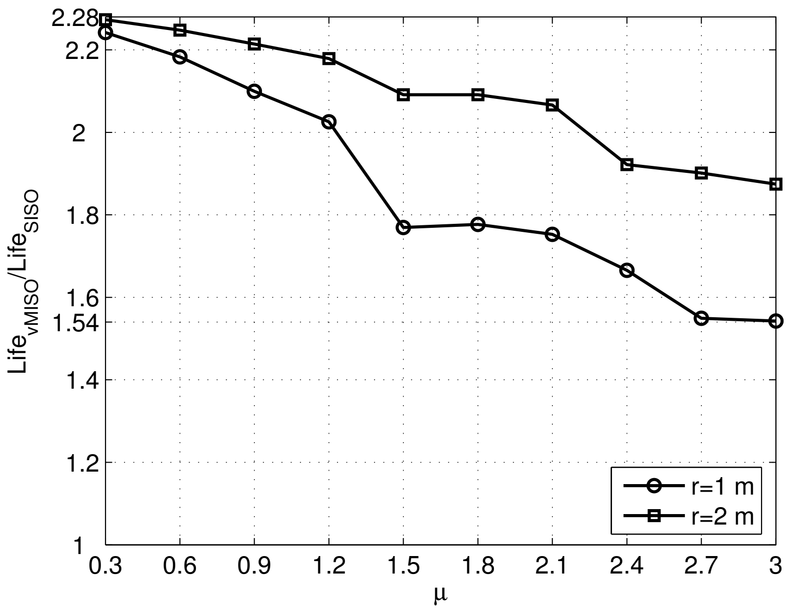


Figure 3.7: Effect of clustering on network lifetime.

nation nodes to the opposite corners of the area. In this simulation each node has an initial energy of $10\mu J$, and cooperation sets and link costs are updated each 60 seconds. Figure 3.6 shows that, vMISO links helps to increase the network lifetime from 10% to 40%.Also, when the network gets denser and the neighborhood radius, $r$, is increased, the ratio of the lifetime with vMISO transmissions to the lifetime with SISO transmissions increases. The reason for this is the same as in the Figure 3.4.

In the second experiment, we consider a network with 20 nodes distributed in an area of 100 m by 100 m. The network consists of uniformly distributed clusters, where each cluster consists of a random number of nodes. The distance of each node to the center of the cluster is exponentially distributed with mean $\mu$. Thus, lower the value of $\mu$, more is the network clustered. There is one source and one destination node in different clusters. Nodes have $20\mu J$ initial energy, and source and the destination nodes have initial energies of 3 times this value. Cooperation sets and link costs are updated each 10 seconds. Since the cooperation set of a node depends on the number of nodes lying in the neighborhood of that node, we investigated the change of lifetime with varying cooperation set radius, $r$. Our results in Figure 3.7 represent the average of 30 instances of random network topologies generated in the aforementioned manner. As depicted in the figure, the network lifetime with vMISO transmissions is more than twice of the network lifetime with SISO transmissions when the nodes are highly clustered. However, as the number of nodes per cluster decreases, then the network lifetime with vMISO transmissions approach to the lifetime with SISO transmissions. Also, when $r$ is increased, it is observed that the lifetime ratio increases, since a node can find better cooperation sets for vMISO transmission in a wider cooperation set range.

# Chapter 4

## CONCLUSION

In this thesis, we studied the energy-efficiency of a general multi-hop vMISO system. We developed a realistic channel and energy consumption model taking into account channel fading and transmitter-side cooperative diversity in ad hoc networks.

In the second chapter, we formulated the minimum total energy consumption problem with vMISO links using the energy consumption model developed. The main advantage of vMISO links that we exploit in this chapter is the increase in the transmission range due to diversity gain. Through the characterization of the optimal vMISO routing policies with respect to the number of cooperating nodes, vMISO transmission ranges and node transmission powers, we showed that the cooperation among a few number of nodes is the most energy-efficient scheme under high node density regime. We designed a new greedy geographical vMISO routing protocol that is also suitable for sparse networks using the results determined under high node density regime. We verified by simulations that our analytical results are correct, and they can be used to develop practical routing algorithms suitable for sparse networks. In addition, our results suggest that by employing vMISO links, higher end-to-end transmission rates are achieved due to the routing paths with lower number of hops compared to the paths found using SISO links. Furthermore, according to our simulations, using vMISO links in sparse networks significantly helps finding a path with greedy geographical routing.

In the third chapter, we investigate the network lifetime maximization problem in networks with vMISO links. We formulated the lifetime maximization problem as a nonlinear program, and then proposed an easy to implement heuristic solution. The heuristic solution can be implemented as a distributed routing algorithm, where each node first determines its cooperating set according to its next hop and the residual energy levels. Given the cooperating set decisions, we determine a cost for each link in the network. A shortest path is calculated over these links, which will be used for pre-specified duration. The cooperating sets and link costs are updated periodically according to the residual node energies. Our results suggest that employing vMISO links can improve the network lifetime more than two times compared to the network lifetime using SISO links. This result is due to the fact that with vMISO links, each transmitting node consumes less energy compared to the SISO links, and the energy consumption is more balanced in the network.

# Bibliography

[1] S.M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Select Areas in Communications*, vol. 16, pp. 1451-1458, October 1998.

[2] J. Chang and L. Tassiulas. Maximum Lifetime Routing in Wireless Sensor Networks." *IEEE/ACM Transactions on Networking*, pp. 609-619, vol 12, no 4, August 2004.

[3] W. Chen, Y. Yuan, C. Xu, K. Liu and Z. Yang, "Virtual MIMO protocol based on clustering for wireless sensor network," *Computers and Communications (ISCC)*, pp. 335 - 340, 2005.

[4] S. Cui, A.J. Goldsmith and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO in sensor networks," *IEEE J. Select. Areas Commun.*, vol. 22, pp. 1089 - 1098, Aug. 2004.

[5] S. Cui, A.J. Goldsmith and A. Bahai, "Cross-layer design of energy-constrained networks using cooperative MIMO techniques," *IEEE Signal Processing.*, vol.86, pp. 1804 - 1814, 2006.

[6] S. Haykin and M. Moher, *Modern Wireless Communications.* Prentice Hall, 2005.

[7] W.R. Heinzelman, A. Chandrakasan and H. Balakrishnan, "Energy efficient communication protocol for wireless microsensor networks," *IEEE Proc. of the 33rd Hawaii Conf. on System Sciences*, 2000.

[8] G. Jakllari, S.V. Krishnamurthy, M. Faloutsos, P.V. Krishnamurthy and O. Ercetin, "A framework for distributed spatio-temporal communications in mobile ad hoc networks," *Proceedings of Infocom 2006*, Barcelona, Spain.

[9] S.K. Jayaweera, "A Virtual MIMO-based cooperative communications architecture for energy-constrained wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol.5, pp. 984 - 989, May 2006.

[10] Y-J Kim, R. Govindan, B. Karp and S. Shenker, "Geographic routing made practical," *In Proceedings of the USENIX Symposium on Networked Systems Design and Imp.*, Boston, MA, May 2005.

[11] J.N. Laneman, "Cooperative diversity in wireless networks: algorithms and architectures," PhD Thesis, Massachusetts Institute of Technology, Cambridge, MA, August 2002.

[12] X. Li, M. Chen and W. Liu, "Application of STBC-encoded cooperative transmissions in wireless sensor networks," *IEEE Signal Processing Lett.*, vol. 12, pp. 134 - 137, Feb. 2005.

[13] W. Liu, X. Li and M. Chen, "Energy efficiency of MIMO transmissions in wireless sensor networks with diversity and multiplexing gains," *IEEE Acoustics, Speech, and Signal Processing (ICASSP '05)*, vol. 4, pp. 897 - 900, March 2005.

[14] A. Khandani, J. Abounadi, E. Modiano and L. Zhang, "Cooperative Routing in Wireless Networks," *Allerton Conference on Communications, Control and Computing*, October, 2003.

[15] A. Paulraj, R. Nabar and D. Gore, *Introduction to Space-Time Wireless Communications*. Cambridge: Cambridge University Press, 2003.

[16] T.S. Rappaport, *Wireless Communications, Principles and Practice.* Prentice Hall, 2002.

[17] Andrew Sendonaris, Elza Erkip, and Behnaam Aazhang, "User cooperation diversity - part I: system description," *IEEE Trans. Communications*, Vol. 51, No. 11, pp. 1927-1938, Nov. 2003.

[18] Andrew Sendonaris, Elza Erkip, and Behnaam Aazhang, "User cooperation diversity - part II: implementation aspects and performance analysis," *IEEE Trans. Communications*, Vol. 51, No. 11, pp. 1939-1948, Nov. 2003.

[19] Andrew Sendonaris, Elza Erkip, and Behnaam Aazhang, "Increasing uplink capacity via user cooperation diversity," in *Proc. of IEEE International Symposium on Information Theory (ISIT)*, Cambridge, MA, Aug. 1998.

[20] B. Sirkeci-Mergen and A. Scaglione, "A continuum approach to dense wireless networks with cooperation," *IEEE INFOCOM*, 2005.

[21] A. Shankar and Z. Liu, "Maximum lifetime routing in wireless ad-hoc networks," *IEEE INFOCOM*, 2004.

[22] W. Su, X. Xia and K.J.R. Liu, "A systematic design of high-rate complex orthogonal space-time block codes," *IEEE Communications Lett.*, vol. 8, no. 6, pp. 38–382, June 2004.

[23] K. Sundaresan and R. Sivakumar, "Routing in ad-hoc networks with MIMO links," *IEEE Proceedings of ICNP*, Nov. 2005.

[24] V. Tarokh, H. Jafarkhani and A.R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1456–1467, July 1999.

[25] D.D. Wackerly, W. Mendenhall and R.L. Scheaffer, *Mathematical Statistics with Applications*. Duxbury, 2002.

[26] W.L. Winston and M. Venkataramanan, *Introduction to Mathematical Programming*. Thomson, 2003.

[27] C. Toh, "Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks," *IEEE Communications Magazine*, June 2001.

[28] S. Singh, M. Woo and C.S. Raghavendra, "Power-aware routing in mobile ad hoc networks," *Mobile Computing and Networking*, pp. 181 - 190, 1998.

[29] K. Kar, T.V. Lakshman, M. Kodialam and L. Tassiulas, "Online routing in energy constrained ad hoc networks," *IEEE Infocom*, 2003.

[30] W. Heinzelman, J. Kulik and H. Balakrishnan, "Adaptive protocols for information dissemination in wireless sensor networks," *In Proceedings of 5th ACM/IEEE Mobicom Conference*, Seattle, WA, August 1999.

[31] R. Mudumbai, J. Hespanha, U. Madhow and Gwen Barriac, "Scalable feedback control for distributed beamforming in sensor networks," *IEEE ISIT*, 2005.

[32] G. Barriac, R. Mudumbai and U. Madhow, "Distributed beamforming for information transfer in sensor networks," *Proceedings of IPSN'04*, 2004.

[33] F. Ng and J.H. Hwu, M. Chen and X. Li, "Asynchronous space-time cooperative communications in sensor and robotic networks," *IEEE ICMA*, 2005.

[34] M. Jananai, A. Hedayat, T.E. Hunter and A. Nosratinia, "Coded cooperation in wireless communications: space-time transmission and iterative decoding," *IEEE Trans. Signal Processing*, Vol. 52, No. 2, pp. 362-370, Feb. 2004.

[35] A. Nosratinia, T.E. Hunter and A. Hedayat, "Cooperative communication in wireless networks," *IEEE Communications Magazine*, October 2004.

[36] F. Ordonez and B. Krishnamachari, "Optimal information extraction in energy-limited wireless sensor networks, *to appear JSAC*.

[37] G. Zussman and A. Segall, "Energy efficient routing in ad hoc disaster recovery networks," *IEEE Infocom*, 2003.

[38] M. Bhardwaj and A.P. Chandrakasan, Bounding the lifetime of sensor networks via optimal role assignments," *IEEE Infocom*, 2002.

[39] K. Kalpakis, K. Dasgupta and P. Namjoshi, "Efficient algorithms for maximum lifetime data gathering and aggregation in wireless sensor networks," *To appear in the Computer Networks Journal*.

[40] S. Lindsey, C.S. Raghavendra, PEGASIS: Power efficient gathering in sensor information systems," *ICC*, 2001.

[41] S. Lindsey, C. Raghavendra and K. Sivalingam, "Data gathering algorithms in sensor networks using the energy-delay metric," *In Proceedings of the IPDPS Workshop on Issues in Wireless Networks and Mobile Computing*, 2001.

[42] I. Maric and R.D. Yates, "Cooperative multicast for maximum network lifetime," *IEEE JSAC, Special Issue on Wireless Ad Hoc Networks*, June 2004.

[43] R. Ramanathan, "On the performance of ad hoc networks with beamforming antenanas," *Proceedings of ACM MOBIHOC*, 2001.

[44] M. Takai, J. Martin, R. Bagrodia and A. Ren, "Directional virtual carrier sensing for directional antennas in mobile ad hoc networks," *Proceedings of ACM MOBIHOC*, 2002.

[45] R. Roychoudhury, X. Yang, R. Ramanathan and N.H. Vaidya, " Using directional antennas for medium access control in ad hoc networks," *Proceedings of ACM MOBICOM*, Sept. 2002.

[46] L. Bao and J.J.Garcia-Luna-Aceves, "Transmission scheduling in ad hoc networks with directional antennas," *Proceedings of ACM MOBICOM*, 2002.

[47] G. Jakllari, T. Korakis and L. Tassiulas, "A MAC protocol for full exploitation of directional antennas in ad-hoc wireless networks," *Proceedings of ACM MOBIHOC*, 2003.

[48] K. Sundaresan and R. Sivakumar, "A unified MAC layer framework for ad-hoc networks with smart antennas," *Proceedings of ACM Mobihoc*, 2004

[49] K. Sundaresan, R. Sivakumar, M.A. Ingram and T.-Y. Chang, "A fair medium access control protocol for ad-hoc networks with MIMO links," *Proceedings of IEEE INFOCOM*, 2004.

[50] L. Meier, P. Blum and L. Thiele, "Internal synchronization of drift-consistent clocks in ad-hoc sensor networks," *Proc. of ACM MOBIHOC* , 2004.

[51] D. Bertsekas and R. Gallager, *Data Networks*, Prentice-Hall, Upper Saddle River, NJ, 1992.