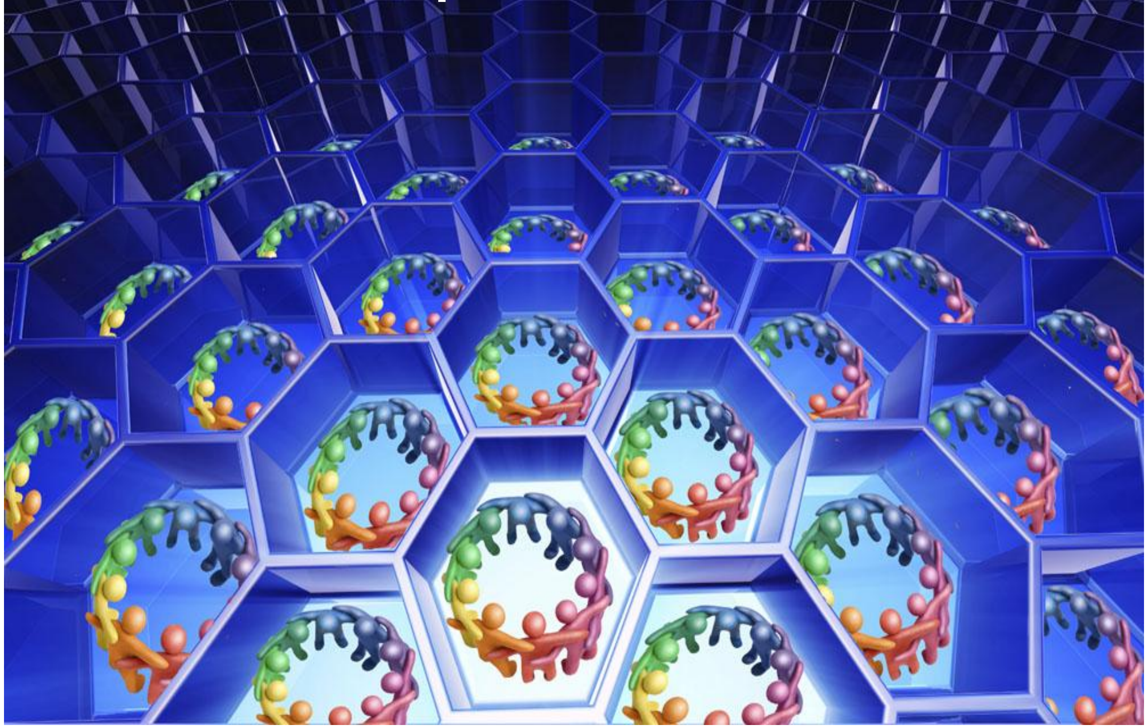
Cooperative Communications and Networking

Chapter 17

Broadband Cooperative Communications

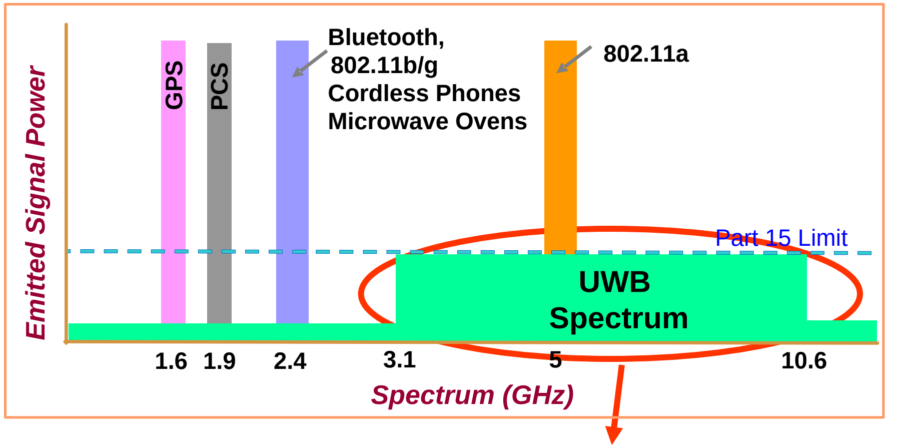


Outline

- Introduction and motivations
- System model
- Cooperative Protocol and Relay Assignment Scheme
- Performance analysis
- Optimum Relay Location
- Simulation results
- Conclusions

Introduction

Ultra-wideband (UWB) offers a great potential for the design of high-speed wireless personal area networks



- Transmitted power level is limited to allow coexistence with other systems
- In broadband communications, OFDM is an effective means to improve performance

[3]

Motivations

Challenge: With the limited transmit power level, how to achieve the desired performance and coverage range?

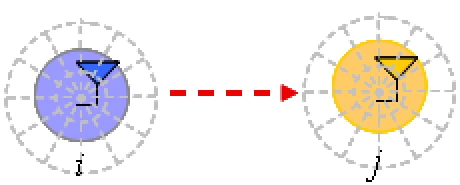
- To improve performance in broadband systems, the fundamental concept of diversity can be applied.

In this chapter, we study an OFDM cooperative protocol that improves performance based on fixed relaying protocol.

- Limited feedback
- Practical relay assignment

System Model

- OFDM Wireless Network i.e. WLAN or WPAN
- Circular cell of radius ρ
- A central node and multiple users, each communicating with the central node
- K users, uniformly located within the cell
- The user's distance $D_{s,d}$
- Uplink scenario $p_{D_{s,d}}(D) = 2D/\rho^2, \quad 0 \le D \le \rho$
- Data packet consists of: preamable, header, and frame payload
- The fade is modeled as zero mean, complex Gaussian random variable
- The channel impulse response from node i to node j can be modeled as:



delay

$$h_{i,j}(t) = \sum_{l=0}^{L} \alpha_{i,j}(l)\delta(t - \tau_{i,j}(l))$$

[5]

System Model

- Consider OFDM with N subcarriers, then we can express the channel frequency response as:

$$H_{s,d}(n) = \sum_{l=0}^{L-1} \alpha_{s,d}(l) \exp(-j2\pi n \tau_{s,d}(l)/N)$$

- The received signal at subcarrier *n* of destination *d* from source user *s* can be modeled as:

$$y_{s,d}(n) = \sqrt{P_{nc} \kappa D^{-v}{}_{s,d}}\, H_{s,d}(n) x_s(n) + z_{s,d}(n)$$

- P_{nc} is the transmitted power N_0
- $x_s(n)$ denotes an information symbol
- $z_{s,d}(n)$ is an additive white Gaussian noise with zero mean and variance

[6]

System Model

- Let each information symbol have unit energy. For a given distance between source and destination, the received signal-to-noise ratio SNR for the *n-th* subcarrier can be given by:

$$\zeta_{s,d}^{(n)} = P_{nc} \kappa D_{s,d}^{-v} \, | H_{s,d}(n) |^2 \, / \, N_0$$

- In case of direct transmission between two nodes the are D, apart the maximum average mutual information in a subcarrier *n* is:

$$I^{(n)}(D_{s,d}) = \log(1 + \zeta_{s,d}^{(n)})$$

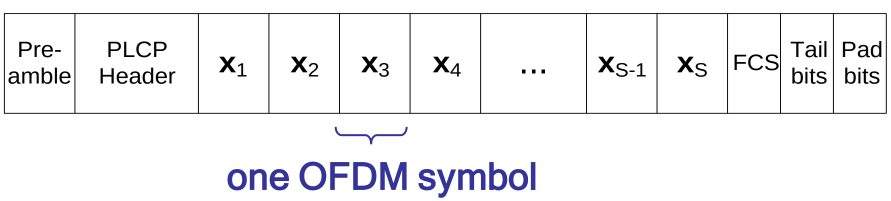
- Let R denote a rate for each subcarrier, then the probability that a subcarrier is in outage can be given by

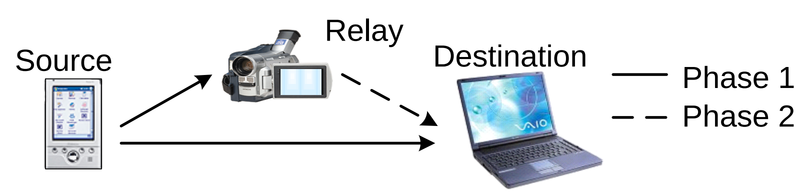
$$P_{out}^{D}(D_{s,d}) = \Pr(I^{(n)}(D_{s,d}) \le R) = \Pr(\zeta_{s,d}^{(n)} \le 2^R - 1)$$

[7]

Cooperative protocol and relay Assignment Scheme

- Phase 1: Each user transmits its packet to the destination (central node) and the packets are also received at the delay
- The destination performs channel estimation using the OFDM pilot symbols, then broadcasts the indices of the subcarriers whose symbols are not received successfully.
- Phase 2: The relay decodes the source symbols that are unsuccessfully received at the destination via direct transmission, then forwards the decoded information to the destination.
- The protocol makes efficient use of the available bandwidth by allowing the relay to forward the information of multiple sources in one OFDM block





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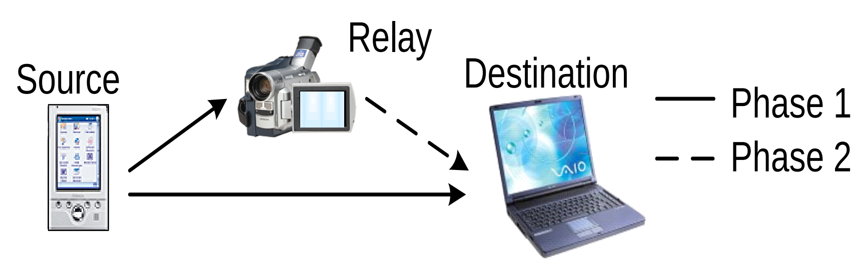
Cooperative protocol and relay Assignment Scheme

- Assume a relay is assigned to help *k* users,
- In phase 2, how will the destination know which relay subcarriers carry information of which users?
- Additional overhead vs. Fixed relay assignment scheme
- Fixed relay assignment scheme: if n_i subcarriers of user *i* are in outage, then in phase 2, the relay can use the first n_1 subcarriers to transmit the data of user 1 and so on.

Pre-amble	PLCP Header	$\mathbf{x}_1$	$\mathbf{x}_2$	$\mathbf{x}_3$	$\mathbf{x}_4$	…	$\mathbf{x}_{S-1}$	$\mathbf{x}_S$	FCS	Tail bits	Pad bits

one OFDM symbol



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Cooperative protocol and relay Assignment Scheme

- In phase 1, the received signals at the destination and the relay are

$$y_{s,d}(n) = \sqrt{P_c \kappa D_{s,d}^{-v}} H_{s,d}(n) x_s(n) + z_{s,d}(n)$$

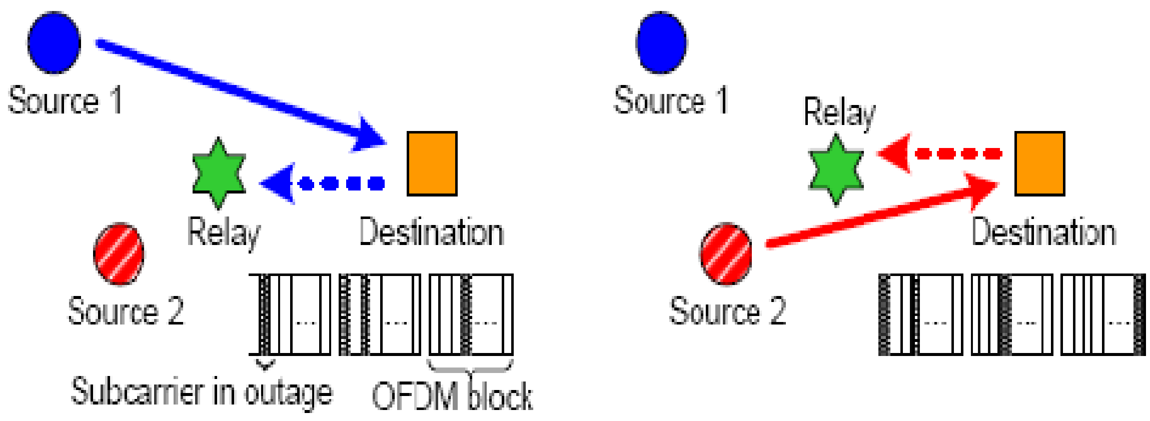
$$y_{s,r}(n) = \sqrt{P_c \kappa D_{s,r}^{-v}} H_{s,r}(n) x_s(n) + z_{s,r}(n)$$

- In phase 2, the signal received at the destination from the relay is

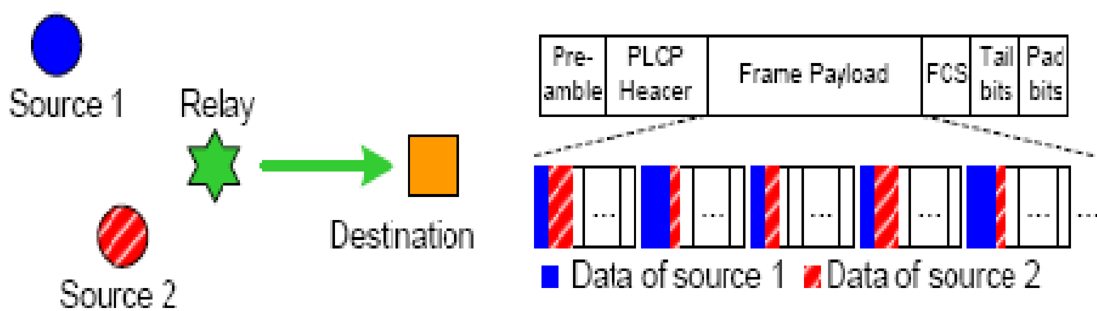
$$y_{r,d}(n) = \sqrt{P_c \kappa D_{r,d}^{-v}} H_{r,d}(n) \tilde{x}_s(n) + z_{r,d}(n)$$

[10]

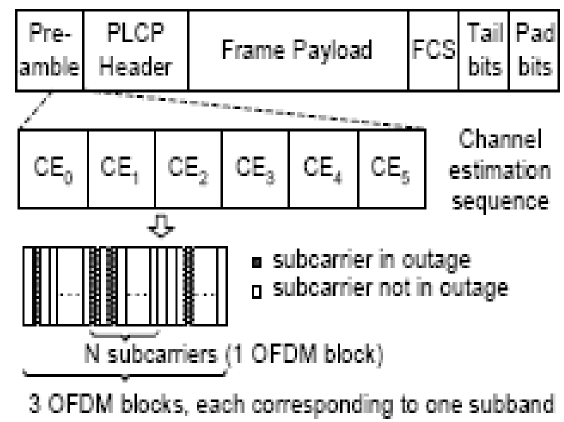
Cooperative protocol and relay Assignment Scheme



(a) Phase 1: Source transmits information to the destination



(b) Phase 2: Relay forwards source information to the destination



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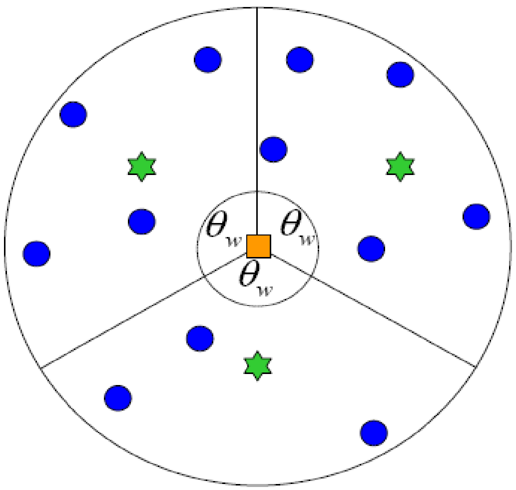
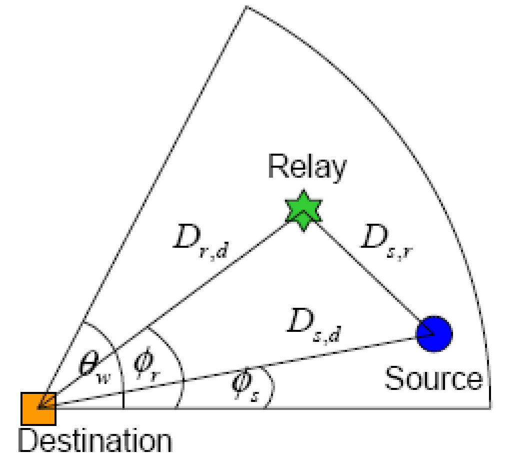
Cooperative protocol and relay Assignment Scheme





An example of relay assignment for a multi-user OFDM system: a cell with three relays

Let W denote the number of relays in a circular cell. The relay assignment is as follows:

- The cell is equally divided into W sectors, each with a central angle $2\pi/W$
- One relay is assigned to help users within each sector
- In each sector, the relay is placed at an optimum relay location which minimizes the outage probability for all possible source-destination pairs

[12]

Performance Analysis

- Outage probability in non-cooperative mode: channel resources (time and frequency) divided among K users

$$P_{out}^{D}(D_{s,d}) = \Pr(I^{(n)}(D_{s,d}) \le R) = \Pr(\zeta_{s,d}^{(n)} \le 2^{R} - 1)$$

- In cooperative mode, the same channel resources are divided among K + W users, thus the mutual information in each subcarrier is given by

$$K/(K+W)I^{(n)}(D_{i,j})$$

- which corresponds to the event

$$|H_{i,j}(n)|^{2} \le \frac{(2^{(K+W)R/K} - 1)N_{0}}{\kappa P_{c}} D_{i,j}^{-v} \cong \beta D_{i,j}^{-v}$$

Performance Analysis

- Under the described protocol, the average probability that a subcarrier is in outage can be expressed as

$$P_{out} = \sum_{k=0}^{K} P_{out|k} \Pr(k\ users\ in\ the\ \sec tor)$$

- Where $P_{out|k}$ denotes the outage probability per subcarrier given k users are in the sector

$$\Pr(k\ users\ in\ the\ \sec tor) = \binom{K}{k}\left(\frac{1}{W}\right)^{k}\left(1-\frac{1}{W}\right)^{K-k} = c(k)$$

- $P_{out|k}$ can be determined as follows. In the case the relay has available resources to help forward the source information, the outage event in subcarrier n is equivalent to the event

$$\Phi = (\{I^{(n)}(D_{s,d}) \le \tilde{R}\} \cap \{I^{(n)}(D_{s,r}) \le \tilde{R}\}) \cup (\{I^{(n)}(D_{s,d}) \le \tilde{R}\}$$
$$\cap \{I^{(n)}(D_{r,d}) \le \tilde{R}\} \cap \{I^{(n)}(D_{s,r}) > \tilde{R}\})$$

Performance Analysis

- $\tilde{R} = (K+W)R/K$ Note, the events in the union are mutually exclusive

$$\Pr(\{I^{(n)}(D_{i,j}) \le \tilde{R}\}) = \Pr(|H_{i,j}(n)|^2 \le \beta D_{i,j}{}^{v}) = 1-\exp(-\beta D_{i,j}{}^{v})$$

$$P_{out}^{C} = \left[1-\exp\left(-\frac{(2^{\tilde{R}}-1)N_0 D_{s,d}^{v}}{\kappa P_c}\right)\right]\left[1-\exp\left(-\frac{(2^{\tilde{R}}-1)N_0}{\kappa P_c}(D_{s,r}^{v}+D_{r,d}^{v})\right)\right]$$

$$P_{out}^{D} = \Pr(I^{(n)}(D_{s,d}) \le \tilde{R}) = 1-\exp\left(-\frac{(2^{\tilde{R}}-1)N_0 D_{s,d}^{v}}{\kappa P_c}\right)$$

$$P_{out|k} = P_{out}^{C}(1-Q|_k) + P_{out}^{D} Q|_k$$

- $Q|_k$ is defined as the probability that a source subcarrier that is in outage is not helped by the relay

[15]

Performance Analysis

- $Q|_k$ can be determined as follows. Consider a sector with *k* users, each transmitting information in *N* subcarriers during one OFDM symbol period.
- The total number of *k*N subcarriers (in k OFDM symbol periods) are used to transmit information from all k users in the sector.
- Given that x out of *k*N subcarriers in outage, the probability that a subcarrier in outage is not helped by the relay is $(x-N)/x \;\; for \; N+1 \le x \le kN$

$$Q|_k = \sum_{x=N+1}^{kN} \frac{x-N}{x} \Pr(x \; out \; of \; kN \; subcarriers \; in \; outage)$$

$$\Pr(x \; out \; of \; kN \; subcarriers \; in \; outage) = \binom{kN}{x} \left(P_{out}^{D}\right)^{x} \left(1-P_{out}^{D}\right)^{kN-x}$$

[16]

Performance Analysis

$$P_{out} = (1-\exp(-\beta D_{s,d}^{v}))\left[1-\exp(-\beta(D_{s,r}^{v}+D_{r,d}^{v}))(1-g(D_{s,d}))\right]$$

$$g(D_{s,d}) = \sum_{k=1}^{K} c(k)Q|_{k}$$

- The average outage probability can be determined by averaging over the distribution of the user's distance. We assume the users are uniformly distributed within the cell.

$$p_D(D \mid 0 \le \phi_s \le \phi_W) = \frac{2D}{W\rho^2}, 0 \le D \le \rho$$

$$\overline{P}_{out} = \frac{1}{\pi\rho^2}\int_0^{\rho}\int_0^{\frac{2\pi}{W}}\left[1-e^{-\beta(f^{v}(D_{s,d},\phi_s)+D_{r,d}^{v})}(1-g(D_{s,d}))\right]\times D_{s,d}(1-e^{-\beta D_{s,d}^{v}})d\phi_s dD_{s,d}$$

[17]

Performance Analysis

- Use Genie-Aided relay assignment scheme to find lower bound.
- Optimum distance between the relay and the destination

$$D_{s,r} = D_{s,d} - D_{r,d}$$

- The optimum relay location for a source-destination pair can be obtained by solving

$$D^*_{r,d} = \arg \min_{D_{r,d}} \{1 - \exp(-\beta((D_{s,d} - D_{r,d})^v + D^v_{r,d}))(1 - g(D_{s,d}))\} s.t. 0 \le D_{r,d} \le D_{s,d}$$

$$D^*_{r,d} = D_{s,d} / 2$$

- By substitution $D^*_{r,d} = D_{s,d} / 2$

$$D^*_{s,r} = D_{s,d} - D^*_{r,d} = D_{s,d} / 2$$

$$P_{out} \ge (1 - \exp(-\beta D^v_{s,d}))\left[1 - (-\beta D^v_{s,d} / (2^{v-1}))(1 - g(D_{s,d}))\right]$$

Optimum Relay Location

- Based on the average outage probability
- Users are uniformly located in the cell
- Optimum relay location is the line that divides the central angle into two equal parts

$$\phi_r^* = \theta_w / 2$$

- Next find the optimum relay distance
- Take the first derivative of $\overline{P}_{out}$ with respect to $D_{r,d}$
- Approximate location can be shown to be

$$\overline{D}_{r,d} = \overline{D}_{s,d} / 2$$

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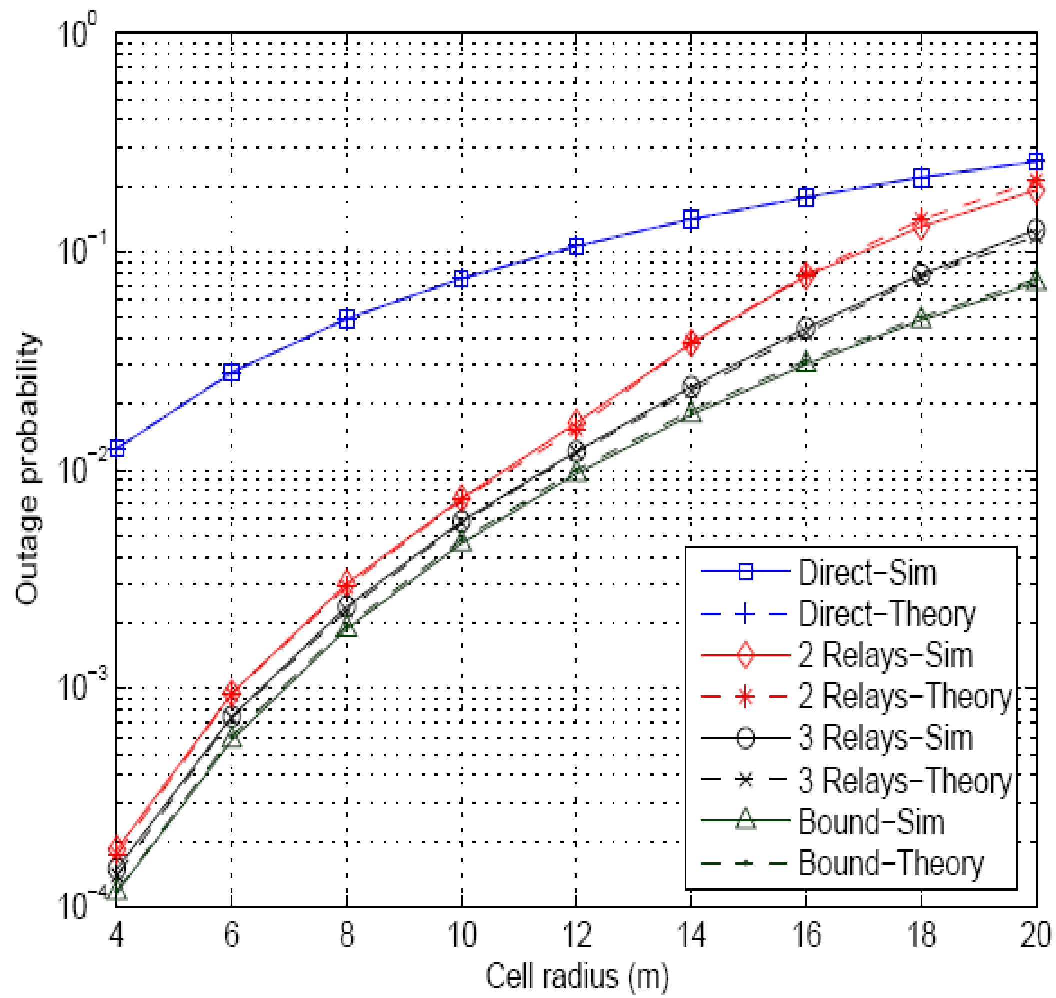
Simulation and Results

- WLAN scenario
- 64 subcarriers
- R = 1 bit/s/Hz per user
- 10 users



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Simulation and Results

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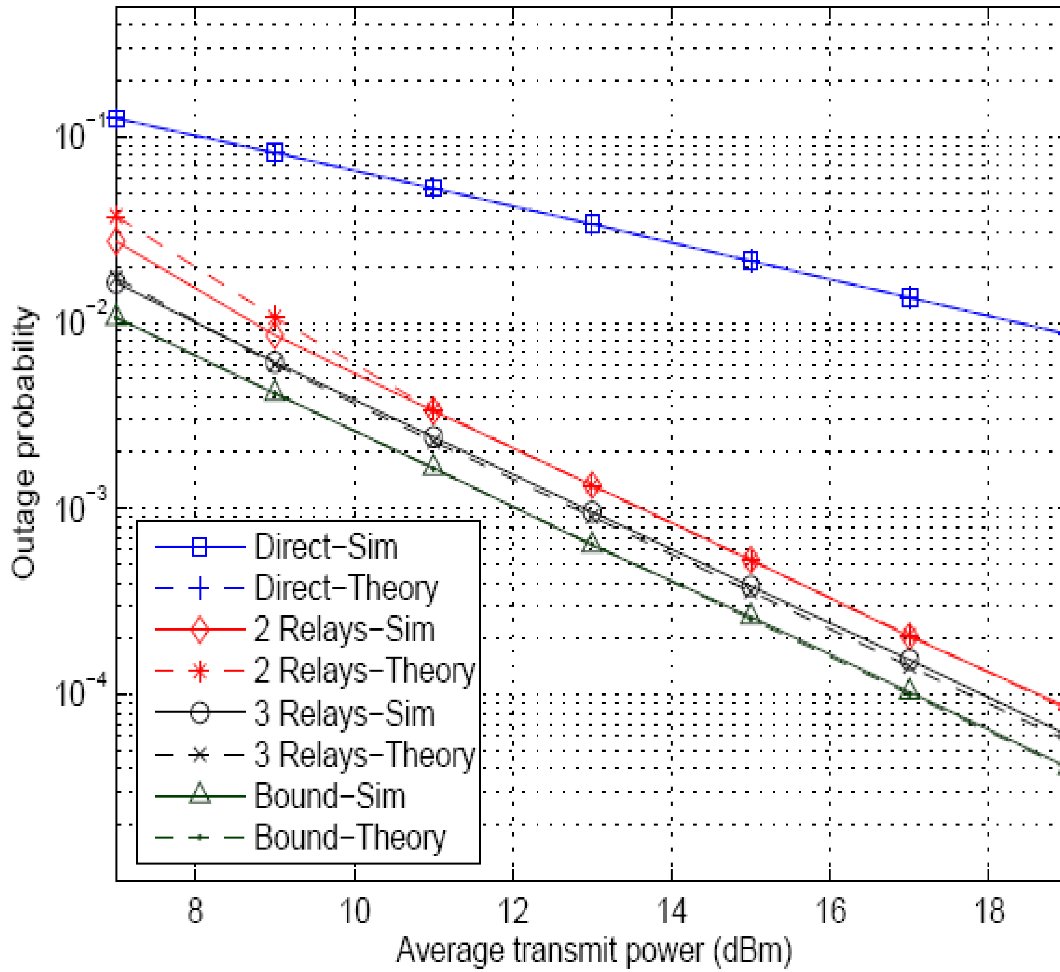

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Conclusions

- Bandwidth efficient protocol for multi-user OFDM systems
- Destination broadcasts subcarrier indices that are in outage
- Relay forwards only the source symbols in those subcarriers
- Data of multiple sources in one OFDM symbol
- Relay assignment algorithm described
- Optimum relay location determined