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Research Article

OFDMA Cellular Networks with Opportunistic Two-Hop Relays

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We investigate the benefits of two-hop opportunistic relay in time division duplex (TDD) OFDMA cellular network configurations. The paper starts with a short analytical model for the two-hop opportunistic relay. The model expresses the probability of finding a suitable relay node in the presence of lognormal fading and it allows the computation of the expected number of out-of-coverage nodes, as well as the end-to-end spectrum efficiency increase due to opportunistic relaying. The paper then presents results for Monte Carlo simulations of opportunistic relay in some realistic scenarios. Specifically, the simulations consider two scenarios. The first scenario uses the propagation model and a wide-area 19-cell configuration specified in 802.16 OFDMA cellular standard evaluation methodologies. In the second scenario, a Manhattan-like 19-cell topology is used. Our simulations show 11% to 33% in throughput increase when the opportunistic relay technology is used. Our results evaluate the benefits of the opportunistic relay in both scenarios in terms of coverage extension and throughput increase.

1. Introduction

The use of relays to extend or improve throughput and coverage is a well-covered subject in literature. First introduced by the European Telecommunication Standards Institute (ETSI) in 1996 [1, 2], the concept of Opportunity-Driven Multiple Access (ODMA) is defined as a UMTS communications relaying protocol standard. ODMA has been adopted by the 3rd Generation Partnership Project (3GPP) to improve the efficiency of UMTS networks using the TDD mode. In ODMA each mobile phone can act as a repeater so the call reaches its destination via a number of hops. Unfortunately, the concept was never implemented in a product. The concept of relaying was recently further developed in the IEEE 802.16j standard [3, 4].

A number of papers are devoted to the performance of relay systems. In [5], the authors use a 3D Markov model to evaluate the impact of ODMA radio resource management for packet transmissions in the UMTS Terrestrial Radio Access Network (UTRAN). In paper [6], the authors analyze the capacity of ODMA in relation to the coverage of a cell. It is shown that after the coverage limit of a non-ODMA UTRAN Time Division Duplex (TDD) system has been reached, ODMA will provide enhanced coverage. The coverage extension of WiMax (802.16) cellular networks is addressed in [7], and the UL performance of an IEEE 802.16j system is investigated in [8]. In this paper, the authors use two-hop relaying for forwarding information from out-of-coverage mobile subscribers to the base station (BS). Using simulations, they show that the two-hop relay will increase the cell radius at the expense of cell throughput. In [9], the authors use a Monte Carlo simulation to investigate the throughput increase in a TDD CDMA cellular multi-hop configuration. Both uniform and nonuniform traffics are investigated. Using simulations, the authors show that the throughput gain becomes insignificant for more than 3 hops.

In our paper, we analyze the concept of two-hop opportunistic relay as a means of attaining throughput increase in 802.16 OFDMA networks. This type of relaying is termed "opportunistic" because it takes place only when the end-to-end throughput is increased by relaying relative to the single hop connection. The concept of opportunistic relay is different from the fixed relay approach proposed in 802.16j. By opportunistic relaying, we mean communication between a base station (BS) and a mobile station (MS) via another MS that serves as a relay. In the opportunistic relaying approach, two MSs can directly communicate via an inband mobile-to-mobile (M2M) connection. The opportunistic relaying concept is related to the hybrid networks presented in [10–14]. In these papers, the authors define the hybrid networks as cellular networks augmented with ad hoc M2M connectivty. The cited papers though do not investigate the system capacity of the hybrid solutions. In [15], the authors offer an asymptotic analysis of the capacity of hybrid networks under a fixed interference range and k-nearest-cell routing strategy in the absence of lognormal fading.

Although our paper considers a network similar to those in [7, 16], we have several novel contributions in our paper. A new analytical model is proposed for opportunistic relay, with the coverage increase analyzed in terms of out-of-coverage subscribers and not in terms of cell radius increase. The spectrum efficiency increase is studied in more realistic environments specified in the IEEE 802.16m evaluation methodology. In addition, the end-to-end link throughput increase is also investigated.

The paper is organized as follows. In Section 2, we propose a new analytic model for two-hop opportunistic relays. Section 3 is based on the proposed analytical model that gives some insights into two-hop relaying in cellular networks. In Section 4, we present our simulation results. Section 5 describes some real system implementation issues. Finally, we draw conclusions in Section 6. This paper extends our previous effort presented in [17].

2. Analytic Aspects of Opportunistic Relaying

Simply speaking, opportunistic relaying stands for relaying when there is a benefit and a relay is available. An opportunistic relay is a two-hop topology consisting of a base station (BS), a mobile station relay (RS) that performs the relay, and a mobile station that becomes relayed (MS). In the proposed approach, all MSs are capable of relaying data to and from other MSs. Therefore, each MS can potentially become an RS.

To analyze the benefits of two-hop opportunistic relays, we consider an OFDMA 802.16 cellular network. The uplink and the downlink are assumed to work independently as specified in 802.16 standards. An RS uses time division duplexing to forward data to and from BS. The mobile-to-mobile connection between RS and MS takes place in a separate subframe called the ad hoc zone. This subframe is proposed as an addition to the standard 802.16 frame which consists of downlink and uplink subframes.

We start by developing a simple analytical model for the two-hop opportunistic relay. In this paper, we use the term *direct link* to indicate the link between a base station and a mobile relay station or to indicate the link between BS and a mobile subscriber; we use the term *mobile-to-mobile link* to indicate the link between a relay station and a mobile station. In our theoretical model, an opportunistic relay is activated in the absence of external interference if the following three conditions are simultaneously satisfied.

(i) Direct link received power at the MS is less than an arbitrary value α, that is, $Pwr_{\text{BS-MS}} < \alpha$. This value corresponds to the the minimum received power for cellular coverage and is equivalent to a spectrum efficiency ζ, that is, SE $< \zeta$ (obtained via Shannon law). The Spectrum Efficiency (SE) is defined as the throughput per subcarrier in bits/s/Hz units or equivalently as bits/symbol/subcarrier units.

(ii) Direct link received power at the RS is Δ watts above the cellular coverage limit α, that is, $Pwr_{\text{BS-RS}} > \alpha + \Delta$ watts, which corresponds to SE $> \zeta + \rho$ bits/s/Hz. In other words, the direct link spectrum efficiency at RS is at least ρ bits/s/Hz greater than the direct link SE at MS.

(iii) Mobile-to-mobile (M2M) link received power at MS is $Pwr_{\text{RS-MS}} > \delta$ watts, which corresponds to spectrum efficiency SE $> \varphi$ bits/s/Hz.

The received power at the receiver is the result of the difference between the transmitted power and the sum of the propagation pathloss and the lognormal fading. In other words,

$$P_{\text{RX}} = P_{\text{TX}} - P_{\text{Loss}}(d_0) - 10\gamma \log_{10}\frac{d_1}{d_0} + \chi, \qquad \chi \sim N(0,\sigma), \tag{1}$$

where P_{RX} represents the received power at distance d_1 from transmitter; P_{TX} and P_{Loss} represent the transmit power and, respectively, the power loss for the reference distance d_0 (usually one meter). The coefficient γ represents the pathloss exponent and χ denotes the lognormal fading that has a normal distribution with zero mean and standard deviation σ. In fact, a more accurate model of the lognormal fading is a Gaussian random 2D field with a given decorrelation distance d_{corr}. In other words, the correlation between the fading values at any two arbitrary points depends only on their relative distance $|d|$. We use for the correlation coefficient the model $R = \exp((-|d|/d_{\text{corr}})\log 2)$, which was first proposed in [18].

Observe that in the absence of interference, the received power P_{RX} expressed in dB is a normal random variable due to lognormal fading. The corresponding random variables $x_1 = Pwr_{\text{BS-MS}}$ and $x_2 = Pwr_{\text{BS-RS}}$ are correlated and their correlation is distance dependent. The M2M received power $x_3 = Pwr_{\text{RS-MS}}$ is not correlated with the other two random variables, but is actually distance-based self-correlated. The joint normal distribution of these three random variables can be written as follows:

$$f(x) = \frac{1}{(2\pi)^{3/2}|\Sigma|^{1/2}} \exp\Big(-(x-\mu)^T \Sigma^{-1}(x-\mu)\Big) \tag{2}$$

where Σ represents the covariance matrix and μ represents the vector of the average received powers (in dB) from the BS at the MS, from the BS at the RS, and, respectively, from the RS at the relayed MS as follows:

$$\begin{aligned} \mu_1(d_1) &= P_{\text{TX}} - P_{\text{Loss}}(d_0) - 10\gamma \log_{10}\frac{d_1}{d_0}, \\ \mu_2(d_2) &= P_{\text{TX}} - P_{\text{Loss}}(d_0) - 10\gamma \log_{10}\frac{d_2}{d_0}, \\ \mu_3(r) &= P_{\text{TX}} - P_{\text{Loss}}(d_0) - 10\gamma_3 \log_{10}\frac{|r|}{d_0}. \end{aligned} \tag{3}$$

The covariance matrix

$$\Sigma = \begin{bmatrix} \sigma_1^2 & \sigma_1^2 \exp\left(\dfrac{-r}{d_{\text{corr}}}\right) & 0 \\ \sigma_1^2 \exp\left(\dfrac{-r}{d_{\text{corr}}}\right) & \sigma_1^2 & 0 \\ 0 & 0 & \sigma_3^2 \end{bmatrix}, \quad (4)$$

where r represents the distance between MS and RS, d_{corr} represents lognormal decorrelation distance for the direct link (usually 50-meters), σ_1 represents the standard deviation of the lognormal fading of the direct link (5–8 dB), and σ_3 represents the standard deviation of the lognormal fading of the M2M link (8–10 dB). In our model, there is no correlation between direct link lognormal fading and the M2M lognormal fading.

Using the above notations, the probability of MS located at distance d_1 from BS to relay through a station RS located at distance d_2 from BS and r from MS, given that MS is in low coverage, $(x_1 < \alpha)$ becomes

$$P_{\text{relay}}(d_1, d_2) = \frac{\int_0^{\alpha}\int_{\alpha+\Delta}^{\infty}\int_{\delta}^{\infty} f(x_1, x_2, x_3)dx_1 dx_2 dx_3}{(1/\sqrt{2\pi}\sigma_1)\int_0^{\infty} \exp\left(-(x_1 - \mu_1(d_1))/\sigma_1\right)^2 dx_1}, \quad (5)$$

where $d_2 = \sqrt{d_1^2 - 2d_1 r\cos\theta + r^2}$, $\theta \in [0, 2\pi)$, $r \in [0, R]$.

If the users' distribution is modeled by a spatial Poisson process, the probability of existence of k users in area A is $P(n = k) = (\lambda A)^k e^{-\lambda A}/k!$, where λ represents the user density in unit area. If A defines an area element in polar coordinates given by $rd\theta dr$, the probability of k users (MS) existence in the element area is $P(n = k) = (\lambda rd\theta dr)^k e^{-\lambda rd\theta dr}/k!$. Each of these users has a probability of being a relay equal to $P_{\text{relay}}(d_1, r, \theta)$. Therefore, if there are k users in the unit area element, the expected number of relays is $E(N_{\text{relays}} \mid \text{users} = k) = kP_{\text{relay}}(d_1, r, \theta)$. The expected number of relays in the area element is given by

$$\begin{aligned} E\left(N_{\text{relays}}(rd\theta dr)\right) &= \sum_k P(\text{users} = k) E\left(N_{\text{relays}} \mid \text{users} = k\right) \\ &= \sum_k \frac{(\lambda rd\theta dr)^k e^{-\lambda rd\theta dr}}{k!} kP(d_1, r, \theta) \\ &= P(d_1, r, \theta)\sum k \frac{(\lambda rd\theta dr)^k e^{-\lambda rd\theta dr}}{k!} k \\ &= P(d_1, r, \theta)\lambda rd\theta dr. \end{aligned} \quad (6)$$

The expected number of all potential relays surrounding MS located at an arbitrary distance d_1 from the BS is expressed as

$$\overline{N}_{\text{relays}} = \int_0^R \int_0^{2\pi} \lambda r P_{\text{relay}}(d_1, r, \theta) d\theta\, dr. \quad (7)$$

This number must be equal or greater than one in order for an opportunistic relay to take place.

The analytic approach allows the definition of a number of metrics of interest for the opportunistic relay scenario. The *number of out-of-coverage* MS (in the absence of opportunistic relay) in the cell radius is given by the number of mobiles in a cell radius having the received signal strength lower than the minimum threshold value α:

$$N_{\text{OOC}} = \frac{1}{\sqrt{2\pi}\sigma_1}\int_0^{R_{\text{cell}}} 2\pi\lambda x \int_0^{\alpha} \exp\left(-\frac{(x_1 - \mu_1(d_1))}{\sigma_1}\right)^2 dx_1\, dx. \quad (8)$$

The *number of relayed out-of-coverage* MS is given by:

$$\begin{aligned} N_{\text{OOC-Relayed}} = {} & \frac{1}{\sqrt{2\pi}\sigma_1}\int_0^{R_{\text{cell}}} 2\pi\lambda x I\left(\overline{N}_{\text{relays}}(x)\right) dx \\ & \times \int_0^{\alpha} \exp\left(-\frac{(x_1 - \mu_1(d_1))}{\sigma_1}\right)^2 dx_1, \end{aligned} \quad (9)$$

where the function I is defined as

$$I(n) = \begin{cases} 1 & \text{if } n \geq 1, \\ 0 & \text{if } n = 0. \end{cases} \quad (10)$$

The relative spectrum efficiency increase is defined as

$$\begin{aligned} \frac{\text{SE}_{\text{relayed}} - \text{SE}_{\text{notrelayed}}}{\text{SE}_{\text{notrelayed}}} &> \frac{((\zeta + \rho)\varphi/\zeta + \rho + \varphi) - \zeta}{\zeta} \\ &= \frac{\varphi\rho - \zeta^2 - \zeta\rho}{\zeta(\zeta + \rho + \varphi)}. \end{aligned} \quad (11)$$

The condition for a positive SE increase gives the limits of direct link SE $\phi\rho - \zeta^2 - \zeta\rho > 0 \rightarrow \zeta \in [0((-\rho + \sqrt{\rho^2 + 4\rho\phi})/2)]$.

3. Opportunistic Relay Insights

To gain insight into the opportunistic relay behavior, we start with a simple analysis of the preceding analytical results by neglecting the lognormal fading and assuming that spectrum efficiency is given by the well-known Shannon capacity expression.

$$\text{SE} = \log_2\left(1 + \frac{P_{\text{TX}}(d/d_0)^{-\gamma}}{\omega kT}\right), \quad (12)$$

where ω represents the frequency bandwidth, k is the Boltzman constant, and T is the absolute temperature. Furthermore, we consider that the MS expected coverage radius r is fixed. This value is derived from the minimum control rate required between MS and its relay as a function of the separation distance. When MS is opportunistically relayed to increase its throughput, it selects from its coverage area the MS with the best direct link SNR and then verifies the conditions for the throughput increase (provided in Section 2) are satisfied. If the expected throughput increase is satisfactory, the MS uses the opportunistic relay. Otherwise it uses the direct link to the base.

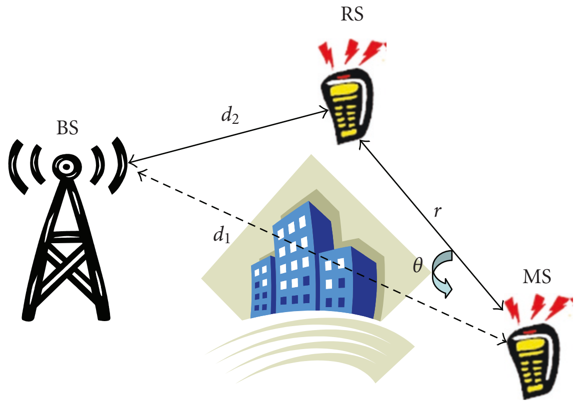

FIGURE 1: Opportunistic mobile relay.

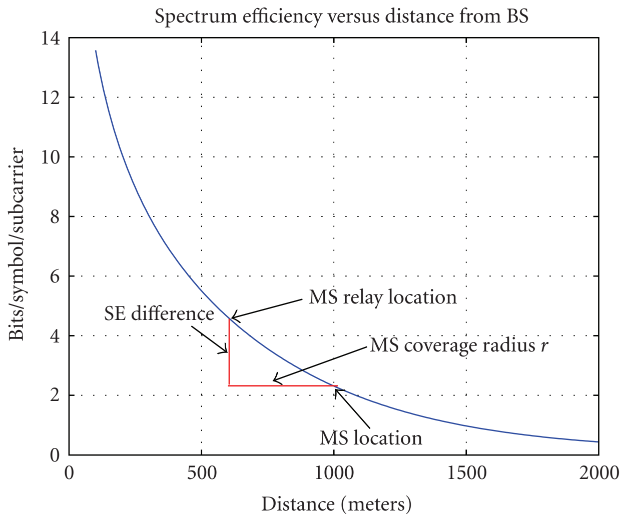

FIGURE 2: The average SE as function of distance.

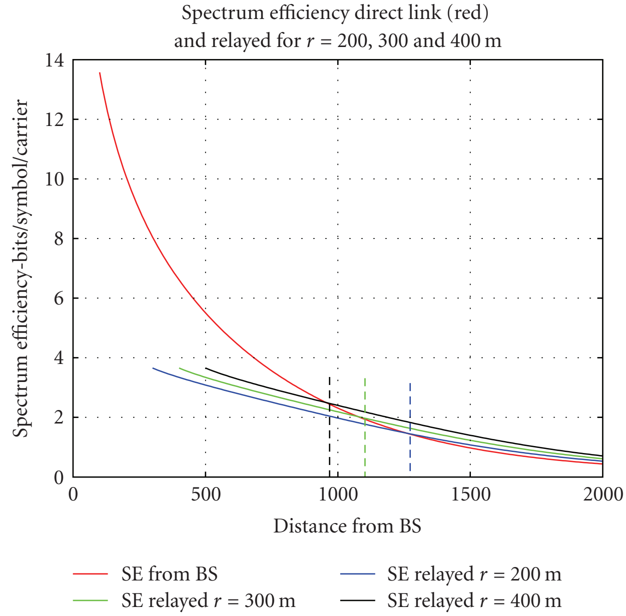

FIGURE 3: MS coverage radius impact to end-to-end SE for opportunistic relay.

Figure 2 shows the rate as a function of distance from BS in the absence of lognormal fading. The exponential curve from Figure 2 is derived from (12). Figure 3 shows the spectrum efficiency (SE) for the direct link (SE from BS) and for the end-to-end opportunistic relay case (SE relayed). The RS-MS M2M link has minimum required SE = 5 bits/symbol/carrier. The relay (RS) is selected in a limited radius (r) around the MS. The figure shows the end-to-end SE for $r = 200$, 300, and 400 m. In this figure the lognormal fading is not considered.

From Figure 3, notice that only stations far from BS benefit from opportunistic relaying. For MS, it is advantageous to use the direct link when it is close to the BS and to use the opportunistic relay when it is close to the cell border. The second observation is that a shorter M2M radius r corresponds to a lower increase in the end-to-end spectrum efficiency. The shorter the M2M radius, the farther the MS must be from the BS to benefit from an opportunistic relay.

In Figure 3, we observe for instance, that MS with coverage range of 300 m will start relaying when they are farther than 1100 m from BS, while those MS with M2M radius of 200 m start relaying when they are farther than 1250 m from BS. Also, MS with a lower M2M coverage will have less overall throughput gain.

Opportunistic relaying becomes more attractive in the presence of lognormal fading. In Figure 4, the lognormal fading spreads the spectrum efficiency values above and below the average direct link pathloss curve (i.e., SE from BS (average)). Therefore, there are more chances for stations with poor coverage to find an attractive relay in their vicinity. As a function of distance, the pathloss (in dB) between BS and MS (or RS) has a normal distribution. Therefore there is a 31% probability that in one location MS has a direct link SNR one σ dB higher than the average SNR for that location, where the 31% probability corresponds to one σ deviation from the average in a normal distribution. On the other hand, at the same location, in the presence of lognormal fading there is a 31% chance that MS receives one σ dB lower SNR than the average SNR for that distance.

Figure 4 shows the SE curves for the direct link in the presence of lognormal fading. The figure shows the SE for the average pathloss (SE from BS average) and the SE of one σ deviations of the pathloss below and above the average (SE from BS 31% high, SE from BS 31% low). In addition, the same figure shows the end-to-end SE curve when the relay (RS) experiences a lognormal fading less than one σdeviation lower than average and the distance RS-MS is not limited (SE with RS pathloss limited). A second end-to-end SE curve represents the end-to-end SE when the relay (RS) is selected from all the potential relays in a radius $r <$ 300 m of MS (SE radius limited < 300 m), that is the relays's pathloss is not limited by the one σdeviation constraint as in the previous curve. Users with average or lower direct link spectrum efficiency benefit more from relaying while mobile

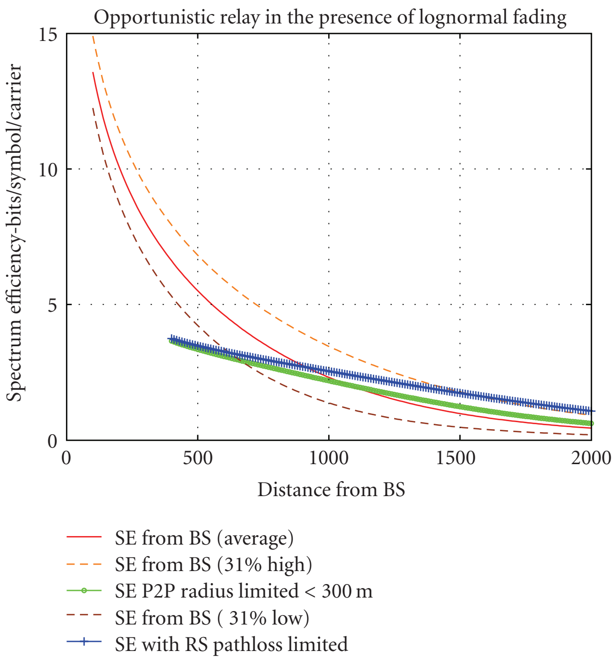

Figure 4: SE for opportunistic relay in the presence of lognormal fading.

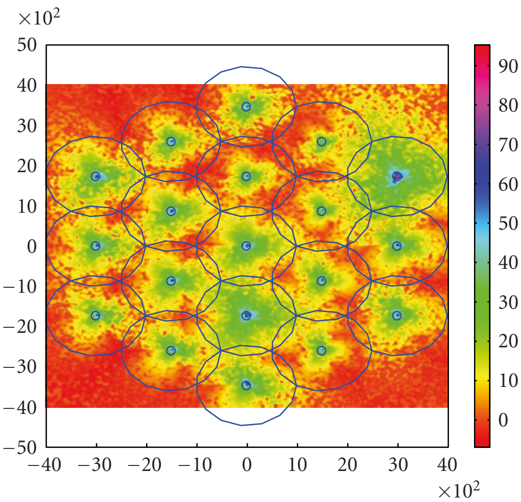

Figure 5: 19-cell configuration, SINR snapshot.

subscribers with a higher SE can become relays for other MS. In the presence of lognormal fading relaying becomes efficient at closer distance from BS (around 650 m in this figure). When there is no constraint of the M2M radius (r), the pool of the potential relays is increased and a better relay can be selected. In this case even the MS with a good direct link starts relaying. However, in real life the M2M relaying radius is reduced by the propagation conditions between the RS and MS. Both the RS and the MS are relatively low height (1.5 m) and therefore the propagation range is shorter.

One also observes that those users farther from the BS have a larger benefit from the opportunistic relaying and have a relative higher increase in the spectrum efficiency. For instance, in the presence of the lognormal fading at a distance of 1600 m from the BS, the users with average spectrum efficiency could double their SE, while low SE users at the same distance could triple their SE when relaying.

4. Simulation Results

The concept of opportunistic relay was implemented in Monte Carlo simulations using a Matlab based system simulator. The system configuration and parameters were chosen to be representative of typical system deployments, although the cell sizes vary by operator and by environment. Most parameters were recommended by the IEEE 802.11m Evaluation Methodology Document (EMD) [19].

The simulator models a system configured with 1000 m cell radius in a 19-cell topology (Figure 5). Each cell has three sectors and a 70 degree antenna beamwidth serves each sector. 2×2 MIMO is assumed for both the BS and MS. Base station antenna height is 32-meters, and MS height is 1.5-meters. The carrier frequency is 2.5 GHz. The total bandwidth is 10 MHz divided into 48 subchannels. The MS transmit power is 23 dBm and is spread over a subset of all 48 subchannels, while the BS transmits at 33 dBm over all subchannels. The simulations use a composite of an exponential path-loss [19] and log-normal fading model. Lognormal fading for direct link had a standard deviation of 8 dB and decorrelation distance of 50-meters and it was expressed as the weighted sum of a common component to all cell sites and an independent component for each cell site. The Rayleigh fading is implemented via the SNR curves used to calculate SE.

The simulations used two system environments for the pathloss and user distribution. The first environment uses a statistical model of a metropolitan system deployment that is representative of typical BS to MS direct link. The model associated with this type of environment gives a good first order approximation of the system performance, but requires artificial constraints or unrealistic expression of the propagation between MS and RS. The second environment attempts to enhance the propagation characteristics of an urban area where some of the RS-MS (opportunistic) link connections experience severe pathloss found around street corners and through one or more building walls. In addition, the second environment allows the use of the idle (inactive) users, while in the first environment the relaying is done by active users; that is users that are already established a call.

The pathloss from BS to MS is defined in the 802.16m Evaluation Methodology Document (EMD) [19] as the baseline test model for urban/suburban pathloss as follows:

$$\mathrm{PL(dB)} = 40\left(1 - 4 \times 10^{-3} h_{\mathrm{BS}}\right)\log_{10}(R) - 18\log_{10}(h_{BS}) + 21\log_{10}(f) + 80 \quad (13)$$

In addition, the pathloss for the M2M link is an exponential pathloss with a randomly selected pathloss exponent from the set 2.4, 3.1, and 4.2. These exponents correspond

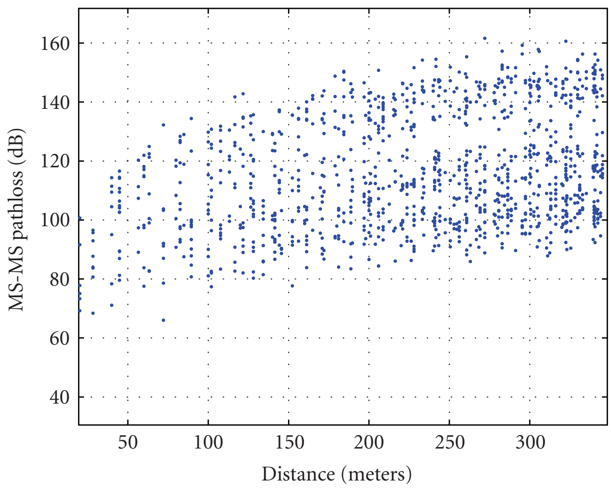

Figure 6: MS to MS pathloss versus distance.

to line of sight propagation below the tree canopy, above the tree canopy and respectively non-line of sight propagation. The lognormal (shadow) fading for the M2M link has standard deviation of 6 dB and it was implemented as the sum of two lognormal components each corresponding to the lognormal fading around each end of the M2M link. Figure 6 presents a snapshot of the MS-MS pathloss versus distance in the presence of lognormal fading.

The M2M pathloss exponents were estimated from RF propagation measurements in a suburban environment; the transmitter and the receiver antennas were at 1.5-meters height and they were placed on perpendicular streets at various distances from the street's intersection.

In each drop, a number of active users were uniformly placed in the simulation space. Each active user evaluates its direct link spectral efficiency, versus the relayed spectral efficiency and selects another active user as a relay if it potentially improves its end-to-end spectral efficiency. A threshold of -0.86 dB corresponding to bits/symbol/subcarrier was used to distinguish between in coverage and out of coverage nodes. In order to better capture the out of cell interference, the results were collected only in the central cluster of 7 cells.

The benefits of the opportunistic relays in terms of the number of out of coverage (OOC) users and respectively the cell average throughput increase are presented in Table 1. The throughput increase is a function of the increase in spectral efficiency for a relayed connection versus a direct link connection of the MS with the BS. Figure 7 shows the cumulative distribution (CDF) of the spectrum efficiency distribution for the opportunistic relay use versus the non-relayed scenario.

The second system simulation environment was selected to represent a Manhattan like topology. The Manhattan style environment consists of a 100 m street grid with buildings occupying the space between streets. The Winner pathloss model from the 802.16m EMD [19] was used for outdoor to indoor building penetration from BS to MS as follows:

$$\mathrm{PL(dB)} = \mathrm{PL}_b + \mathrm{PL}_{\mathrm{tw}} + \mathrm{PL}_{\mathrm{in}} \quad (14)$$

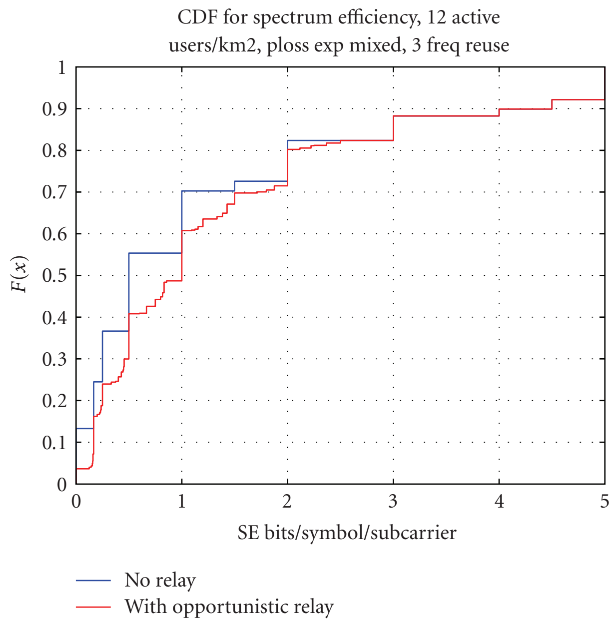

Figure 7: Spectrum efficiency for opportunistic relays -CDF plot.

Table 1: OOC and throughput increase.

User density in radius 1000 m	OOC before relaying	OOC after relaying	Average cell throughput increase
8 users/km^2	5.0%	1.5%	11.3%
12 users/km^2	5.0%	0.9%	14.4%
16 users/km^2	5.0%	0.6%	17.2%

where $\mathrm{PL}_b = \mathrm{PL}_{B1}(d_{\mathrm{out}} + d_{\mathrm{in}})$, $\mathrm{PL}_{\mathrm{tw}} = 14 + 15\,(1 - \cos(\theta))^2$, $\mathrm{PL}_{\mathrm{in}} = 0.5 d_{\mathrm{in}}$ and $3\,\mathrm{m} < d_{\mathrm{out}} + d_{\mathrm{in}} < 1000\,\mathrm{m}$, $h_{\mathrm{BS}} = 12.5\,\mathrm{m}$, $h\mathrm{MS} = 3n_{\mathrm{Fl}} + 1.5\,\mathrm{m}$, $n_{\mathrm{Fl}} = 2$. PL_{B1} is also defined in the 16 m EMD as the baseline test model for urban/suburban pathloss as described previously. In addition, a M2M pathloss model was used for MS-MS connections based on field measurements for Line-of-sight (LOS), around a street corner, and into buildings. Pathloss exponents are used in an exponential pathloss model between the MSs corresponding to these environments. When the environment contains streets and buildings, the specific exponents used for this environment were 2.4 LOS, 3.1 around corner <100 m, 4.2 > 100 m around corner, 4.2 through one exterior wall, and 5.1 through multiple exterior walls.

Two system configurations were modeled with this Manhattan environment to contrast two typical system deployments. The first configuration consists of cells with a 750-meter radius and a BS transmits power of 46 dBm in a 19-cell topology as specified in 802.16m EMD. The second configuration increases the cell size to 1000-meter radius while lowering the BS transmit power to 33 dBm.

To evaluate the potential for opportunistic relay, we assume that the total user density is made up of idle and active users. This means that both active and idle MS are permitted to relay. Initially, for these simulations we chose a

Table 2: Throughput increase as function of system configuration.

Configuration	Average throughput gain (all connections)	Relay-only throughput gain
46 dBm BS Tx Power, 750 m cell radius	52%	171.13%
33 dBm BS Tx Power, 1000 m cell radius	80%	207.73%

total user density (active + idle) of 160 users/km^2 where 5% of users are assumed to be active in a call (i.e., 8 users/km^2). Later, we increase the percent of active users.

As with the first environment, results are tabulated from the center cluster of 7 cells from the 19-cell configuration of this Manhattan environment. In this simulation environment, all MS that are out-of-coverage are excluded from the results. Out-of-coverage uplink occurs when MS cannot reach BS at QPSK rate with 4 repetitions. Out-of-coverage direct link occurs when BS cannot reach MS at QPSK rate with 2 repetitions.

The benefit of opportunistic relay for the 750-meter cell radius configuration is contrasted with the benefits of opportunistic relay for the 1000-meter cell radius configuration in Table 2. In Table 2, the results for the average system throughput gain are presented, as well as the relay-only throughput gain when examining only the benefit to the relayed users. The average throughput gain represents the spectral efficiency of all users in the system assuming that all users in the system are in the best connection configuration (i.e., relaying when it is beneficial) versus all users in the system are in direct link (none of them relayed). The relay-only gain is computed the same way except that only the users that end up being relayed are considered in the gain analysis.

Additional results for the 750-meter cell configuration are shown in Figures 8 and 9. Figure 8 illustrates the distance between MS and its relay (RS) for all relay occurrences. Figure 9 illustrates the distance between every MS that is relayed and its BS that ultimately serves that MS. Figure 8 shows that the distance between the relayed MS and the relay RS is relatively small compared to the distance between the relayed MS and the BS, which is presented in Figure 9. Furthermore, Figure 9 shows that not all relayed MS are at the fringe of the cell. We noticed in our simulations that the cell radius does not impact the distance between the relayed MS and the relay MS, however, an increase in cell radius from 750 m to 1000 m causes the mean distance from relayed MS to BS to shift proportionally to the increase in cell radius.

Assuming a fixed user density of 160 users/sq. km, the impact of increasing the percent of active users is shown in Table 3.

Unlike the results shown in Table 1 from the first statistically modeled simulation environment, we see in Table 3 that while the average throughput increases significantly with relays through idle users, the percent of active users has little impact on the average throughput gain. This is because the number of idle users dominates the user density to provide an opportunistic relay. Consequently, the throughput gains remain constant. We also see that a little less than 50% of the active users are relayed, but only 2–4% of the idle user base is actively performing a relay.

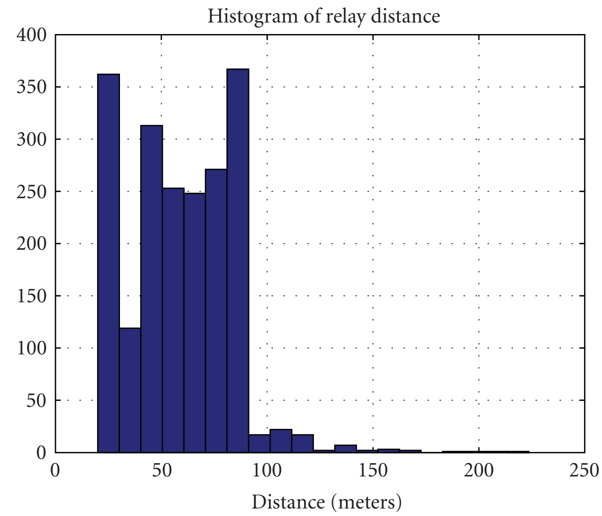

Figure 8: Distribution of the distance between RS and MS.

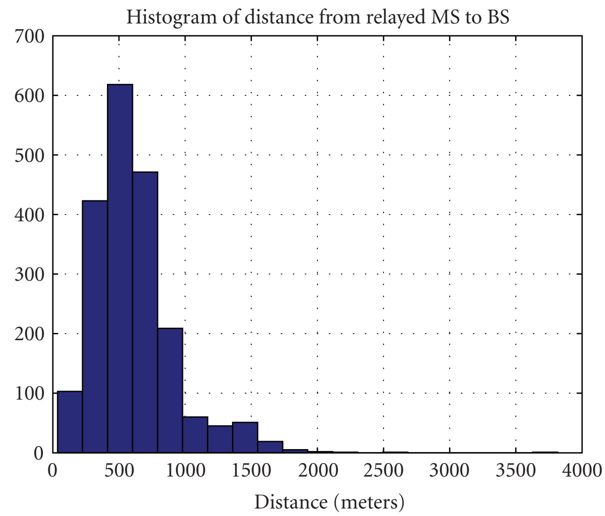

Figure 9: Distribution of the distance between relayed MS and its BS.

Table 3: Throughput increase as function of active user density.

Active users/km^2	Average throughput gain	Active users connections relayed	Idle users performing relay
8	52%	47.69%	2.23%
10	44%	46.6%	2.91%
12	49%	48.11%	3.25%
14	49.5%	47.93%	3.82%
16	45.5%	47.56%	4.37%

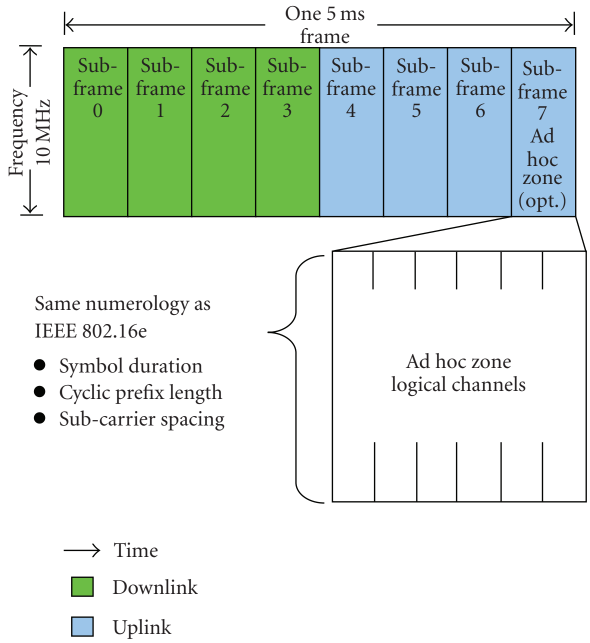

Figure 10: Frame structure.

5. Real System Implementation Issues

The results presented in Section 4 were obtained from a system simulator designed to model IEEE 802.16m system deployments. A couple different approaches are possible to enable Opportunistic Relay connections with the physical layer frame structure of IEEE 802.16m. The 802.16m frame structure is divided in time into 8 subframes. The use of these subframes may vary, but one example use divides the subframes evenly between downlink (DL) and uplink (UL) communications. Each subframe consists of 6 symbol times. In a 10 MHz channel bandwidth, the individual subcarriers are divided into 48 subchannels. The 48 subchannels represent the resources that can be allocated to individual users. Multiple subchannels can be allocated per user depending on the number of bits to communicate and the channel conditions of the allocated subchannels.

One approach to enable Opportunistic Relay is to reserve an UL subframe for communications between MS in all opportunistic relay configurations. This UL subframe is designated as an ad hoc zone (AHZ). The presence of the AHZ is determined by traffic requirements for MS relay as well as the overall resource demands for non-relay connections (which have a higher priority for resource allocations). When the traffic demands for opportunistic relay communications are low, the AHZ may not be present in every frame. When the system demand is very high, the AHZ may not be present in any frame. The AHZ is depicted in Figure 10.

The use of an AHZ provides several advantages, but also has some disadvantages. OFDM data symbols in an AHZ can be allocated as logical channels. Logical channels enable a variety of traffic and control uses. For example, a control channel could be implemented to advantageously enable an opportunistic relay communication between an out-of-coverage MS with an in-coverage MS. The AHZ also allows the mitigation of various forms of interference when the AHZ is defined within one of the UL subframes since this would insure that all mobile-to-mobile communications occur at the same time independent other UL and DL transmissions within the system. However, the AHZ does occupy one fourth of all UL resources. When the number of opportunistic relay connections is small, there will be unused UL resources within the AHZ that reduce overall system capacity since the resources cannot be assigned to any other user. Hence, this is the reason for reducing the presence of the AHZ under light and heavy system demands. Finally, the AHZ competes for UL subframe resources with infrastructure relay (i.e., 802.16j) which also occupies a full UL subframe.

Regarding signaling overhead, our proposal utilizes a dedicated Ad Hoc Relay Zone within a single subframe, and this ad hoc zone has two logical channels dedicated for signaling between nodes that perform a relay, nodes that are relayed, or nodes that are involved in a direct link connection. The Ad Hoc Relay Zone is dynamically allocated to match traffic demands for relay and direct link connections. Our analysis shows that the signaling control overhead is 0.65% under optimum conditions and 2.6% under impaired channel conditions. This overhead can be reduced to 0% under heavy system loading where the ad hoc zone is not required.

For these system simulations, the use of an AHZ was assumed. However, an alternate approach to enable Opportunistic Relay allows subchannel resources to be allocated for MS to MS communications within any of the uplink subframes. The advantage of this approach is that no UL resources are wasted when the demand for opportunistic relay is sparse. This reduces the overall complexity of managing system resources. However, the disadvantage of this approach is the inability to enable opportunistic relay to out-of-coverage MS, in other words the opportunistic relay would only be used to improve throughput for MS in poor coverage. An additional disadvantage is the increased likelihood of near/far interference from UL transmissions of non-opportunistic relay connections. This is because the PMP (point-to-multi-point) connections are sharing the same subframe as the mobile-to-mobile connections of the opportunistic relay connections. A future study will contrast the performance of the AHZ approach with the no-AHZ approach.

6. Conclusions

In the present paper, we investigate the benefits of two-hop opportunistic relays in OFDMA cellular networks. The paper presents a simple statistical model for two-hop relay in cellular networks. The proposed model allows the estimation of probability of relaying for throughput increase and coverage extension. The benefits of the opportunistic relays, in terms of coverage increase and end-to-end spectrum efficiency increase, are further studied via realistic

Monte Carlo simulations. Our simulations show 11% to 33% in throughput increase when the opportunistic relay technology is used. Higher gains are observed in city-like environments. In addition, the simulations exhibited a significant reduction in the number of out-of-coverage nodes. Both the analytical model and the computer simulations show that the benefits of cooperative relays are increasing with the increase in user density. We hope that our results provide a better understanding of the opportunistic relay technology in cellular networks and will contribute to the acceptance of this technology in the cellular standards.

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