MOBILE RELAY SELECTION SCHEMES FOR TWO-HOP WIRELESS LINKS AND THEIR THROUGHPUT PERFORMANCE COMPARISON

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ABSTRACT

This paper focuses on two-hop wireless communications where mobile terminals act as relay stations. Five alternative methods for mobile relay selection are proposed and their throughput performance is compared. Multilevel link qualities and capacities are determined according to two distance dependent path loss models within a circular cell system model. The numerical results show that selecting a relay that minimizes the length of the second wireless hop is generally a good strategy. Also, as a set of candidate relays grows the average achievable throughput improves accordingly.

I INTRODUCTION

Wireless network resources can be utilized more efficiently and flexibly when relays are used as complementary elements in addition to conventional cellular structure. This kind of relay-enhanced cellular topology enables wireless two-hop communications where the first hop is a conventional link between the base station (BS) and a mobile station (MS) and the second hop is a relay link between two MSs. Opportunistic relay links provide local extensions to cell coverage near the cell edge. In addition, when ever the BS-RS-MS geometry is favorable, the transmit powers can be minimized and the link adaptation optimized at the same time. Insightful discussion on relaying concepts can be found, e.g., in [1]. Standardization is also active on relay enhancements, for example in IEEE 802.16’s Relay Task Group [2]. European research project WINNER+ [3] and its predecessors have seriously considered relay deployment solutions for IMT-Advanced. Cost efficiency of the fixed relay enhanced networks has been evaluated, e.g., in [4] and [5]. More recent performance examples of the relay deployment via system level simulations are available in [6].

Instead of fixed relays this paper focuses on mobile relay selection schemes in circular cell and their comparative throughput performance evaluation. Four link adaptive modulation levels (and thereby four throughput classes) are assumed. They are defined upon path loss dependent signal-to-noise ratio thresholds and respective spatial coverage areas. Mobile stations are used as relays to forward traffic to other mobile stations. The aim is to compare the performance of two-hop links among the proposed relay selection schemes with alternative parameter settings and path loss models.

The reminder of the paper includes the following. Section II defines the system model having subsections for considered path loss models, modulation level break distances, and proposed mobile relay selection algorithms. Section III presents some comparative numerical examples. Finally, the paper is summarized in Section IV to be followed by a brief bibliography.

II SYSTEM MODEL

II.A Path Loss Models

This study adopts WINNER and IEEE 802.16j Relay Task Group non-line-of-sight (NLOS) path loss models [7] and [8], respectively, for propagation modeling. WINNER II C2 NLOS path loss in dB scale is denoted as

\[ PLW(d)[dB] = \left[ 44.9 - 6.55 \log_{10}(h_{BS}[m]) \right] \log_{10}(d[m]) + 33.46 + 5.83 \log_{10}(h_{BS}[m]) + 20 \log_{10}(f[GHz]/5.0) \]  \hspace{1cm} (1)

presuming distance to be in the range of 50 m < d < 5 km, BS antenna height set to \( h_{BS} = 25 \) m and the carrier frequency \( f \) expressed in GHz. In addition, the MS antenna height is assumed to be \( h_{MS} = 1.5 \) m. The corresponding IEEE 802.16j path loss model for NLOS links is written as

\[ PLA(d)[dB] = 38.4 + 35 \log_{10}(d) + 20 \log_{10}(f[GHz]/5.0) - 0.7 h_{m} \] \hspace{1cm} (2)

where antenna height \( h_{m} \) is the lower one of the link ends. For MS-MS links (1) and (2) might be too optimistic since, in spite of NLOS conditions, they generally presuppose the antenna height at the end of the other transmission link to be at least 10 m.

II.B Link Budget Based Break Distances for Variable Throughput Classes

Fig. 1 depicts the assumed circular cell system model where zones of different shades of gray illustrate the four modulation/throughput classes supported by the base station and the relay station. At close proximity of the BS (or RS) the average link quality is adequate for 64-QAM modulation to be applied. Going further away from the BS the signal strength gradually decreases with the distance so that the modulation levels need to be downgraded first to 16-QAM then to QPSK and finally near the cell edge to BPSK. The cell radius is set to distance \( r_1 \) that corresponds the minimum signal-to-noise ratio (SNR) level for successful BPSK communications.

Based on (1) and (2), and other link budget parameters, the switching distances between modulation levels can be solved as

\[ d_{W}[m] = 10^{\frac{A - 34.46 - 5.83 \log_{10}(h_{BS}[m]) - 20 \log_{10}(f[GHz]/5.0)}{44.9 - 6.55 \log_{10}(h_{BS}[m])}} \] \hspace{1cm} (3)
for the WINNER path loss model (1) and
\[ d_i[m] = 10^{-3.84+20 \log_{10}(f_{GHz}/5.0)+0.76} \]  
for the IEEE path loss model (2). In (3) and (4), \( A = P_t - SNR_{th} - N_0 - NF \) where \( P_t \) is the transmit power in dBm, \( SNR_{th} \) denotes the required signal-to-noise ratio in dB, \( N_0 \) is the power spectral density of thermal noise in dBm, and \( NF \) is the receiver noise figure in dB. Link performance parameters of the OFDM system are adopted from [9]. Thereby, the \( SNR_{th} \in (6.4, 9.4, 16.4, 22.7) \) dB for BPSK, QPSK, 16-QAM, and 64-QAM, respectively. Channel coding rates to achieve these targets in [9] have been 1/2 for the lowest three modulation alphabets and 2/3 for 64-QAM. The corresponding link throughput classes are (6.91, 13.82, 27.65, 55.30) Mbps.

II.C Relay Selection Schemes for Two-Hop Links

Let \( \mathbf{d}_{\text{RS-MS}} = [d_{\text{RS-MS}}(1), \ldots, d_{\text{RS-MS}}(N_{\text{RS}})] \) and \( \mathbf{d}_{\text{BS-RS}} = [d_{\text{BS-RS}}(1), \ldots, d_{\text{BS-RS}}(N_{\text{BS}})] \) be \( (1 \times N_{\text{RS}}) \)-distance vectors between the base station and \( N_{\text{RS}} \) relay stations and between the \( N_{\text{RS}} \) SSs and the desired MS, respectively. The proposed five relay selection methods are defined as follows.

**Algorithm 1:** For each iteration find the index of the shortest link of the RS-MS link distance vector, i.e.,
\[ \text{ind}_1 = \arg \min \{d_{\text{RS-MS}}\}. \]  

**Algorithm 2:** For each iteration find the index of the shortest link of the BS-RS link distance vector, i.e.,
\[ \text{ind}_2 = \arg \min \{d_{\text{BS-RS}}\}. \]  

**Algorithm 3:** For each iteration find the index of the shortest BS-MS distance, i.e.,
\[ \text{ind}_3 = \arg \min \{d_{\text{BS-RS}} + d_{\text{RS-MS}}\}. \]  

Then calculate the two-hop throughput according to link distances \( d_{\text{BS-RS}}(\text{ind}_1) \) and \( d_{\text{RS-MS}}(\text{ind}_1) \). In (8), the weighting factor \( w_1 \in [0, 1] \). It is noteworthy that all the previous algorithms are special cases of Algorithm 4. For \( w_1 = 0 \) this algorithm reduces to Algorithm 1 and for \( w_1 = 1 \) to Algorithm 2. For \( w_1 = 0.5 \) it is a linearly scaled version of Algorithm 3 and thereby provides the same minimization result.

**Algorithm 4:** For each iteration find the index of the shortest weighted BS-RS-MS distance, i.e.,
\[ \text{ind}_4 = \arg \min \{w_1 d_{\text{BS-RS}} + (1-w_1) d_{\text{RS-MS}}\}. \]  

In (9), \( U \) denotes a uniformly and independently distributed discrete random variable. Because the link distances are randomized for each iteration the Algorithm 5 could also be implemented by picking any RS index with or without changing it from iteration to iteration.

For all algorithms the next step is to calculate the two-hop throughput and other performance metrics according to link distances \( d_{\text{BS-RS}}(\text{ind}_i) \) and \( d_{\text{RS-MS}}(\text{ind}_i) \) where \( i \in [1, 5] \) denotes the algorithm number. Fig. 1 shows a simple example where different relays are selected for Algorithms 1-3. A common prerequisite for the operation of Algorithms 1-4 is that the network element making the relay selection is aware of the locations of the mobile terminals within the cell (to rank the preference order of them). Information on network topology can be obtained, e.g., from received signal power measurements or from a separate positioning system or application. For Algorithm 5 the sufficient condition is that there is at least one relay station in the coverage area.

II.D Two-Hop Throughput Classes

Assuming that two-hop transmission consumes twice as much radio resources (e.g., time and/or frequency) as a single hop, there is a straightforward relation between the capacities individual links and total throughput, shown as [10]
\[ C_{\text{BS-RS-MS}} = \left( \frac{1}{C_{\text{BS-RS}}} + \frac{1}{C_{\text{RS-MS}}} \right)^{-1} \]  
where \( C_{\text{BS-RS}} \) and \( C_{\text{RS-MS}} \) represent the BS-RS link and RS-MS link capacities, respectively. With four modulation levels there will be altogether ten two-hop throughput combinations that are depicted in Table 1. Therefore, traffic data rates in the cell area fall into these discrete categories depending on the combined two-hop link distances.

![Figure 1: Circular cell system scenario for two-hop links with spatially distributed throughput zones.](image)
Table 2: Key parameters in the numerical examples

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS antenna height $h_{BS}$</td>
<td>25 m</td>
</tr>
<tr>
<td>RS and MS antenna height $h_{RS}$</td>
<td>1.5 m</td>
</tr>
<tr>
<td>BS transmit power $P_{TB}$</td>
<td>37 dBm</td>
</tr>
<tr>
<td>RS and MS transmit power $P_{TR}$</td>
<td>24 dBm</td>
</tr>
<tr>
<td>RS and MS receiver noise figure $N_{FRS}$</td>
<td>9 dB</td>
</tr>
<tr>
<td>Number of relay stations $N_{RS}$</td>
<td>1, 2, 4, 8, 16, 32, 64, 128</td>
</tr>
<tr>
<td>Weighting factor $w_1$</td>
<td>0.1, 0.2 (default), ... , 1.0</td>
</tr>
<tr>
<td>Carrier frequency $f$</td>
<td>5.0 GHz</td>
</tr>
<tr>
<td>Signal bandwidth</td>
<td>100 MHz</td>
</tr>
<tr>
<td>Thermal noise $N_0$</td>
<td>-93.9794 dBm</td>
</tr>
</tbody>
</table>

Table 3: Throughput/modulation class break distances

<table>
<thead>
<tr>
<th>Path Loss Model</th>
<th>64-QAM</th>
<th>16-QAM</th>
<th>QPSK</th>
<th>BPSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>WINNER, BS-RS/MS</td>
<td>38.5 m</td>
<td>57.8 m</td>
<td>90.7 m</td>
<td>110 m</td>
</tr>
<tr>
<td>WINNER, RS/MS-MS</td>
<td>14.5 m</td>
<td>20.2 m</td>
<td>29.2 m</td>
<td>34.2 m</td>
</tr>
<tr>
<td>IEEE, BS-RS/MS</td>
<td>58.8 m</td>
<td>89.0 m</td>
<td>141 m</td>
<td>172 m</td>
</tr>
<tr>
<td>IEEE, RS/MS-MS</td>
<td>25.0 m</td>
<td>37.8 m</td>
<td>60.0 m</td>
<td>73.1 m</td>
</tr>
</tbody>
</table>

III NUMERICAL RESULTS

Some numerical examples will be shown next to illustrate the throughput performance statistics of mobile relay enhanced two-hop communications. Achievable performance of the desired user (i.e., destination of the second hop) is monitored and compared using previously defined relay selection algorithms. Key parameters for the evaluations are collected into Table 2. $N_{RS}$ relay stations only form a set candidate relays without having their own traffic. Thus, the achievable throughput is not affected by multiuser interference in this study. Both the desired MS and candidate RS positions are randomly dropped for each simulation iteration and considered to be spatially uniformly distributed over the circular cell area. Final simulation results are averaged over 100,000 independent runs.

Table 3 depicts the edge distances for switching between achievable throughput classes at different link types and channel models (i.e., solved from (3) and (4) with BS and MS specific parameters from Table 2).

Fig. 2 shows the outage probability curves when the relay selection is done according to Algorithms 1-5 and path loss models (1) and (2). An outage event is accounted for while $SNR_{BS,RS}<6.4$ dB. Both the relay selection method and the relay density in the cell area play an important role in the outage results. It turns out that only the Algorithms 1 and 4 provide satisfactory service probability. Yet, even for them the number of relay stations have to be relatively high to ensure reliable connectivity. Algorithms 2 and 5 are clearly the worst performing ending up in high saturated $P_{out}$ levels irrespective of the number of relays. Algorithm 3 does not do much better.

Figs. 3 and 4 illustrate the first and second moment statistics of throughput performance with Algorithms 1-5 at the same parameter settings as in Fig. 2. The mean throughput performance follows the same trend that was seen previously for outage probability. Algorithms 1 and 4 (with $w_1 = 0.2$) yield practically identical results for $N_{RS} \leq 16$ after which the Algorithm 4 getting slightly better of the two. Algorithms 3, 2, and 5 are significantly worse in terms of throughput. Standard deviations tend to increase along the RS density and throughput improvement. However, the highest throughput variation is recorded for Algorithm 3. For other algorithms the variation in throughput levels down at the large number of RSs. The clear exception is Algorithm 5 whose performance remains constant and independent of the relay density.

A histogram of the throughput class occurrences with WINNER path loss model and Algorithm 1 relay selection method is presented in Fig. 5. All the possible throughput classes are realized but especially the shares of 6.142 and 11.057 Mbps classes increase drastically as the relay density becomes greater. It should be noted that link outages, i.e., throughput $= 0$ Mbps are omitted here (see Fig. 2). Contributions in high quality links take more prominent role when the number of relay stations becomes larger.

A similar histogram plot for Algorithm 3 is seen in Fig. 6.
Because the average throughput is lower than in the previous case the experienced throughput classes are also quite different. Now the throughput classes are expressed more evenly. Again, the peak concentration occurs at the throughput class of 11.057 Mbps when $N_{RS} = 128$.

The throughput class histogram for Algorithm 5 is shown in Fig. 7. Although it has become evident that this algorithm has the weakest performance, the illustration reveals best the spatial link geometry specific characteristics of the scenario. Namely, the joint area probabilities of BS-RS and RS-MS links providing throughput 4.607, 6.91, 9.214, and 11.057 Mbps are clearly dominant. These results can also be analytically verified.

Fig. 8 depicts how the joint effect of weighting factor and relay density variation modifies the average throughput. In this example, Algorithm 4 is applied with the WINNER path loss model. Clearly, the throughput is best optimized for the weighting factors $w_1 \leq 0.4$. It means that RS-MS link selection should be emphasized over BS-RS link selection. This is mainly due to smaller high throughput coverage areas of RS-MS links and therefore higher sensitivity to link quality losses.

Fig. 9 illustrates the corresponding second moment statistics, i.e., standard deviation among the throughput classes. The peak variance is observed for parameter combination $N_{RS} = 128$ and $w_1 = 0.5$ that was already shown in Fig. 4. Otherwise the surface is relatively smooth, which indicates robustness with respect to parameter tuning.

IV CONCLUSION

Mobile relay extended two-hop link throughput performance was evaluated in circular multi-zone link geometries and two propagation models. Five algorithms were proposed for mo-
bile relay selection based mainly on the link length minimization. These algorithms were compared in terms of throughput statistics and link outage probabilities at variable spatial relay densities. Four level modulation was assumed with two NLOS path loss models. The best strategies turned out to emphasize RS-MS link length minimization. Random relay selection was the only algorithm not gaining from increased number of relays.

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REFERENCES