Relay-Based Network Deployment Concepts for Downloading Data on Move

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Abstract—This paper provides a mathematical framework related to deployment of relay-based network while the user on move. Two basic scenarios, drive-through, and walk-through are used to describe the user mobility in relay-based cellular network. In multi-hop communication, the performance of relay-based network depends on the link budget evaluation for access link as well as relay link. In this work, both the access link and relay link has been characterized by throughput-distance relationship model. These two throughput-distance relationship models have been utilized to develop combined throughput-distance model. Finally utilizing the combined throughput-distance model, the performance of relay enhanced cell has been carried out.

In performance evaluation of relay based network, both average throughput and aggregated throughput have been presented as performance metrics and numerical results are compared in case of single-hop, multi-hop and combined coverage scenario. Finally, we have shown how to select the coverage range and where to position the relay to meet the certain service demand while a mobile user traversing the coverage of relay based network at different velocities.

I. INTRODUCTION

In near future, mobile user will have a realistic alternative to download fixed high data rate services on move in the coverage of relay enhanced cell without the need for a cable to access the network. Multihop relaying technique with infrastructure based cellular is the viable solution to provide these services on go. As a result, in 2006, an amendment was finalized, which enhances IEEE 802.16-2004 standard for adding user mobility, this amendment is known as IEEE 802.16e [2][3]. Moreover, currently further amendment to the IEEE 802.16e and the integration of multi-hop capabilities through the deployment of relays, has been been proposed in 802.16j [4]. In this current amendment new Medium Access Control (MAC) protocol and further enhancement of frame structure as well as terminologies have been harmonized to support mobility in the coverage of relay-based network, which will ultimately pave the way for downloading data on move [5].

There will be various applications of relay based network that can be described by two basic scenarios of user mobility which is shown in Fig. 1, drive-through, walk-through. The drive-through scenario corresponds to high-speed users that pass through the coverage area in seconds, as in a roadway; the walk-through scenario is characterized by slow speed users, such as in a sidewalk or a mall. In this work, both types of mobile users are considered as downloading data on move. Hence a key challenge to the service provider in deploying these relay based wireless networks is capacity planning that making the best use of the available network resources to derive the best return on its investment while at the same time satisfying user service demand. This advocates the need for the development, validation, and analysis of quantitative models to study the performance of relay-based network before it is deployed.

In many cases throughput is considered as the performance metric in performance prediction model to evaluate the performance of wireless network [1]. Throughput is affected by the channel environment such as the distance between transmitter and receiver, fading state of the channel, noise and interference power characteristics and many others [2]. On the other hand, performance of relay-based network depends also on the link budget evaluation for access link and relay link as well as positions of FRSs from the MMR-BS [1]. Hence, considering the effects of all above mentioned parameters to the throughput, each link may be described as simplified throughput-distance model [2]. The purpose of using this throughput-distance model is to treat certain aspects in new radio-network solutions in a general way, while modeling other aspects in more great details.

The carrier-to-interference ratio (CINR) vs. distance rela-
tionship has been used to evaluate the performance of relay-based network in [3]. Throughput performance dependent on distance based data rate of relay-based enhanced cell has been investigated in [4], and [5].

In most of the above mentioned studies, computer simulations are used to evaluate the performance of wireless network. In contrast to this, in this work we attempt to formulate the performance of mobile multi-hop network analytically using throughput-distance models. Therefore, we first develop access link as well as relay link specific throughput-distance models by utilizing channel propagation and usage scenario model. Finally combined throughput-distance will be developed and utilized to evaluate the performance of relay-based network while a mobile user is traversing through the combined coverage area.

The remaining of this paper is structured as follows. In Section II we describe the scenario where a mobile user is traversing through the coverage area of relay enhanced cell. A formulation of throughput-distance model to derive received average throughput and information transferred by relay-based network is addressed in Section III. Numerical examples based on throughput-distance relationship models are also presented and discussed in Section IV. Finally, conclusions are drawn in Section V.

II. DATA DOWNLOAD ON MOVE

A scenario of data download on move in the coverage of relay-based network is shown in Fig. 2. When the user passes through the coverage of relay enhanced cell, the user will experience both single-hop as well as multi-hop communication. In such case traveling distance between entering point and exit point can be segmented into different parts to reduce the per-hop loss.

In single-hop communication the mobile user will served by the MMR-BS, e.g., via access link. On the other hand, in multi-hop communication the user will served by both access and relay links. The data rate are changing according to the channel condition, the closer the user is to the MMR-BS, higher the data rate it receives from it [2]. The size of file that will be downloaded to the users digital storage depends also on the mobile user velocity and placement of the relay.

III. GEOMETRY BETWEEN RINGS

Three co-centric circles are used to represent the different segments of traveling path of a mobile user. Two outer tiers are used to represent the coverage of multi-hop communication whereas the most inner tier represents the coverage of single-hop communication as shown in Fig. 2. The coverage range of the third tier, second tier, and the first tier are $R$, $d$, and $x_s$ respectively. $R$ is the maximum cell range of the combined coverage, $d$ is the distance between MMR-BS and FRS, and $x_s$ is the single dimension switching point between multihop and singlehop transmission.

We utilize Cartesian Co-ordinates $(x, y)$ to describe the locations of mobile user, MMR-BS, and FRS. The MMR-BS is placed at the origin $(0, 0)$. We assume that two FRSs and MMR-BS are aligned along the x axis. FRSs are placed at the right and left side of MMR-BS. The position of both relays are same from the MMR-BS. The traveling angle $\theta$ is created at the centre by entering point and exit point. The traveling distance depends on the traveling angle. The higher the traveling angle longer the traveling distance traveled by the mobile user. For example, the travelling path created by entering point and exit point which is also represented as $D$ can be expressed as

$$D = 2\sqrt{R^2 - L^2}. \quad (1)$$

The minimum distance $L$ between mobile user and the center of combined coverage can be expressed as

$$L = (\cos \frac{\theta}{2})R. \quad (2)$$

Depending on the traveling angle, the mobile user may have either multihop or both multihop and singlehop communications. If the mobile user has multihop communication in that case end to end multihop throughput can be expressed as

$$c_{\text{end-to-end}} = \left(\frac{1}{c_{\text{hop1}}} + \frac{1}{c_{\text{hop2}}}-1\right)^{-1}, \quad (3)$$

where $c_{\text{hop1}}$ and $c_{\text{hop2}}$ are the throughputs in the first-hop and multi-hop respectively.

Two dimensional switching point from singlehop to multihop or vise versa can be expressed as

$$(x_s, y_s) = \left(\frac{c_{\text{end-to-end}}(\frac{d}{R} - 1) + S_{\text{max}}}{c_{\text{end-to-end}} + \frac{S_{\text{max}}}{R}}, S_{\text{max}}(1 - \frac{x_s}{1 + r_{bs}})\right), \quad (4)$$

where $S_{\text{max}}$ is the maximum throughput offered either by MMR-BS or FRS.

For an example, if mobile moves between entering point A and and exit point B. The received average throughput of mobile user crossing the coverage of realy-enhanced cell is then given by

$$S_v(r) = \frac{1}{D} \int_{A}^{B} S(r)dr, \quad (5)$$
where $S(r)$ represents the throughput-distance relationship and $r$ is function of $x$ and $y$. The integral given in (5) is a line integral to calculate the instantaneous throughput along the traveling distance. We can parameterized the location of the mobile as $(x_c(2t-1), y_c)$, where $x(t) = x_c(2t-1), y(t) = y_c$ and $0 \leq t \leq 1$.

However, because of the symmetry in throughput-distance relationship we will consider first sector to calculate the average throughput. In such case, there is no impact on the result. The instantaneous distance $r$ between the center of combined coverage and mobile user can be calculated as

$$r = \sqrt{(x_0 + t(x_c - x_0))^2 + y_c^2},$$

(6)

where $x_0$ and $x_c$ are initial and final points of a particular segment of line in respective tier. For example Substituting (6) in (5), the average throughput between A and B becomes

$$S_w(r) = \int_0^1 S(\sqrt{x_0 + t(x_c - x_0))^2 + y_c^2}) dt,$$

(7)

Secondly, while the mobile user passes through the traveling path CD as shown in Fig. 2. The initial and final points of line segment in tier 3 are:

$$x_3^i = \sqrt{d^2 - y_c^2}$$

(8)

$$x_3^f = r \sin(\theta)$$

(9)

where $x_3^i$ and $x_3^f$ represent the initial and final points in tier 3. The initial and final points of line segment in tier 2 can be calculated as follows:

$$x_2^i = 0$$

(10)

$$x_2^f = r \sin(\theta).$$

(11)

where $x_2^i$ and $x_2^f$ represent the initial and final points in tier 2. Now to calculate the average throughput while the user passes through the outer two tiers can be expressed as

$$S_w = \left\{ \begin{array}{ll}
\int_0^1 S(\sqrt{(x_3^i + t(x_3^f - x_3^i))^2 + y_c^2}) dt, & d < y_c < R \\
\int_0^1 S(\sqrt{(x_2^i + t(x_2^f - x_2^i))^2 + y_c^2}) dt, & x_s < y_c < d \\
\int_0^1 S(\sqrt{(x_1^i + t(x_1^f - x_1^i))^2 + y_c^2}) dt, & 0 < y_c < x_s
\end{array} \right.$$

(12)

Finally, if the user traverses through the path EF, the line segments in the different tiers can be calculated as follows: The initial and final points in the tier 3 will be calculated by using (8) and (9).

The initial and final of the line segment in tier 2 can be calculated as follows:

$$x_2^i = \sqrt{d^2 - y_c^2}$$

(13)

$$x_2^f = r \sin(\theta)$$

(14)

Finally the initial and final point in tier 1 can be calculated as follows:

$$x_1^i = 0$$

(15)

$$x_1^f = \sqrt{b^2 - y_c^2}$$

(16)

Consequently, the average throughput while the user passes through the all tiers can be expressed as

$$S_w = \left\{ \begin{array}{ll}
\int_0^1 S(\sqrt{(x_3^i + t(x_3^f - x_3^i))^2 + y_c^2}) dt, & d < y_c < R \\
\int_0^1 S(\sqrt{(x_2^i + t(x_2^f - x_2^i))^2 + y_c^2}) dt, & x_s < y_c < R \\
\int_0^1 S(\sqrt{(x_1^i + t(x_1^f - x_1^i))^2 + y_c^2}) dt, & 0 < y_c < x_s
\end{array} \right.$$

(17)

The total aggregated throughput $I_t$ which is defined as the total transferred file size from the relay enhanced cell to the mobile user during dwelling time (time within the coverage) $t_{dwell}$ is given by

$$I_t = S_{total} t_{dwell},$$

(18)

where $S_{total}$ is the total average throughput the mobile user will perceive during traversing from entering point to exit point. Total average throughput is defined as the summation of different segments throughputs and dividing it by distance traveled by mobile user. The relationship between traveling distance, dwelling time and velocity $v$ can be expressed as

$$t_{dwell} = \frac{2D}{v},$$

(19)

where $D$ is expressed in meter and $v$ in m/s.

### A. Usage and Channel Model

Usage models differ in terms of the manner the relays are deployed and types of services or performance goals that are trying to be achieved. In this work, fixed infrastructure usage model has been considered. Fixed infrastructure usage model is where relay is fixed at a certain location from the MMR-BS [1]. The scenario system is being operated at 5 GHz band with system bandwidth of 20 MHz. In this work, we have considered 802.16j standard specified access and relay link channel model.

In standard [1], a variety of environment specific channel models have been provided. In this work, the suburban C1 Metropol pathloss model for relay link from 802.16j is chosen. In this case it is assumed that FRS is deployed with good Line of Sight (LOS) back to the MMR-BS. The LOS pathloss model for relay link can be expressed as

$$PL(r_1) [dB] = 42.5 + 23.5 \log_{10}(r_1),$$

(20)

where $r_1$ is the distance in meter between MMR-BS and FRS.

On the other hand, for the access link, we have chosen Non-Line-of-Sight (NLOS) channel model, whose pathloss can be characterized as

$$PL(r_2) [dB] = 38.4 + 35 \log_{10}(r_2) + 0.7h_m,$$

(21)

where $r_2$ is the distance between MMR-BS (FRS) and MS in meter, $h_m$ is the antenna height of FRS.

802.16j supports a variety of modulation and coding schemes. This adaptive modulation and coding scheme is distance dependent. The switching distance between different
modulation techniques for the case in (20) can be expressed as

\[
d_{\text{switch-to}} = 10^{\frac{P_t (\text{dBm}) - 42.5 - N (\text{dBm}) - S N (\text{dB})}{23.5}},
\]

(22)

where signal-to-noise ratio (SNR) is the minimum required value to maintain a certain PHY mode. SNR is the important factor in deciding cell boundary. For dimensioning purposes, in case of downlink (DL), the minimum required SNR at the cell boundary for BPSK modulation is 6.4 dB and the noise power spectral density \( N \) in a 20 MHz band can be calculated as [6]

![Fig. 3. Derived and linear approximation of throughput-distance models.](image)

TABLE I

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Receiver SNR [dB]</th>
<th>Throughput [Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>6.4</td>
<td>6.91</td>
</tr>
<tr>
<td>QPSK</td>
<td>9.4</td>
<td>13.82</td>
</tr>
<tr>
<td>QPSK</td>
<td>11.2</td>
<td>20.74</td>
</tr>
<tr>
<td>16QAM</td>
<td>16.0</td>
<td>37.65</td>
</tr>
<tr>
<td>16QAM</td>
<td>18.2</td>
<td>41.47</td>
</tr>
<tr>
<td>64QAM</td>
<td>22.7</td>
<td>55.30</td>
</tr>
<tr>
<td>64QAM</td>
<td>24.4</td>
<td>62.71</td>
</tr>
</tbody>
</table>

...physical distance. In this linear approximation, in case of derived throughput-distance relationship by linear throughput-distance model. For simplicity and analytical tractability we approximate the effective distance in (22) and (24) and then mapping this effective distance as given in (22) and (24) and then mapping this effective distance to a throughput as outlined in Table I [7]. Furthermore, for simplicity and analytical tractability we approximate the derived throughput-distance relationship by linear throughput-distance relationship. In this linear approximation, in case of relay link, we consider maximum throughput \( S_{\text{max}} \) at distance difference 0 between MMR-BS and FRS and minimum throughput 0 at \( R_{\text{max}} \). We apply also the same rule for access link case. The derived and approximated throughput-distance relationship models both for relay and access link are shown in Fig. 3.

The approximated linear throughput-distance relationship for relay link (MMR-BS \( \longleftrightarrow \) FRS) can be expressed as

\[
S_{BF}(r_1) = \begin{cases} 0.019r_1 + 62.21, & 0 < r_1 < R_{\text{max}} \\ 0, & \text{otherwise.} \end{cases}
\]

(25)

where \( R_{\text{max}} \) is the maximum cell range in relay link. and for access link (MMR-BS,FRS \( \leftrightarrow \) MT) as

\[
S_{BM}(r_2) = \begin{cases} 0.20r_2 + 62.21, & 0 < r_2 < r_{\text{max}} \\ 0, & \text{otherwise.} \end{cases}
\]

(26)

where \( r_{\text{max}} \) is the maximum cell range in access link. By using (25) and (26) and for a particular distance between MMR-BS and FRS. Combined throughput distance relationship model can be expressed as

\[
S(r) = \begin{cases} \frac{a_1 r + b_1}{x_s}, & 0 < r < x_s \\ \frac{a_2 r + b_2}{x_s - d}, & x_s < r < d \\ \frac{a_3 r + b_3}{d - r_{\text{bs}}}, & d < r < 2r_{\text{bs}} \end{cases}
\]

(27)

where \( a_1 \) and \( b_1 \) in (27) can be expressed as

\[
a_1 = -\frac{(62.21 - y_s)}{x_s}, \quad b_1 = 62.21.
\]

(28)

(29)

Similarly \( a_2, b_2, a_3 \) and \( b_3 \) in (27) can be expressed as

\[
a_2 = -\frac{(y_s - c_{\text{end-to-end}})}{(x_s - d)}, \quad b_2 = (-ax_s + y_s).
\]

(30)

(31)

\[
a_3 = \frac{(c_{\text{end-to-end}})}{(d - r_{\text{bs}})}, \quad b_3 = (c_{\text{end-to-end}} - a_3d).
\]

(32)

(33)

Finally to calculate the average throughput in particular line segment of the combined coverage can be obtained by putting the value of \( x_c, x_0 \) and \( y_c \) in the underlying equation

\[
s_{\text{avg}} = a_i\left(\frac{y_c^2 \ln(x_c + \sqrt{x_c^2 + y_c^2}) + x_c \sqrt{x_c^2 + y_c^2} - x_0 \sqrt{x_c^2 + y_c^2}}{2(x_c - x_0)}\right) + b_i,
\]

(34)

where \( x_0, x_f \) and \( y_c \) are calculated in Section 3 and the values of \( a_i \) and \( b_i \) are segment specific as calculated in above equations.

In multi-hop communication the received average throughput of mobile user can be expressed as

\[
S_{\text{total}} = s_3 \cdot (x_3 - x_2) + s_2 \cdot (x_2 - x_1) \cdot (x_c).
\]

(35)
where $S_3$ and $S_2$ are the average throughputs of segments in tier 3 and in tier 2 respectively.

The total average throughput while a user is served by both single-hop and multi-hop communication (in the combined coverage of relay enhanced cell) can be represented as

$$S_{total} = S_3 \cdot (x_3^f - x_3^i) + S_2 \cdot (x_2^f - x_2^i) + S_1 \cdot (x_1^f - x_1^i) \quad (x_c).$$

where $S_1$ is the average throughput of segment in tier 1.

### IV. NUMERICAL RESULTS AND DISCUSSION

In this section the throughput performance of relay-based network will be evaluated using combined throughput-distance model which is presented in Section III for two different type of users: walk-through and drive-through. To provide target user demand and fasciate data downloading on move for different type users the impact of position of relay and velocity of the user play an important role on the planning of such relay-based network.

Fig. 4 shows the two dimensional average throughput performance for three different positioned of relay. We evaluate the performance while the relay was inside the coverage of MMR-BS, at the cell edge, and outside the coverage of MMR-BS. It is seen that higher the distance between MMR-BS and FRS the more average throughput degradation in the system. The reason is while the position between MMR-BS and FRS increases the lower rate region in access link and relay link of throughput-distance model is also increased. As a result, both lower rate throughputs contributes a large fall in average throughput. For example, when distance between MMR-BS and FRS is 622 m. A large throughput falls is seen between 700 m to 800 m but this is not the case when FRS is placed inside the coverage (d=180 m) of MMR-BS.

Fig. 5 shows the aggregated capacity performance of walk-through and drive-through user at different velocities. As it is expected, while the velocity of mobile user increases aggregated capacity performance of walk-through and drive-through user decreases. The reason is when the velocity of mobile user increases, the dwelling time of the user in the coverage decreases. As a result, the volume of data to be downloaded is less at the higher velocity. In mixed user cases (walk-throughput, drive-through) service provider should consider the average traffic demand from the specific user and their velocity in providing services. For example to provide 0.48 Gbyte data to the 30 km/h speed drive-through and 3.25 Gbyte data to the walk-through user the FRS is to be placed at 311 m from the MMR-BS.

### V. CONCLUSION

In this work, we develop a methodology to dimension the coverage and capacity of relay-based cellular network. The main objective is to fulfill the service demand of mobile user under various conditions. The main contribution to this approach is to develop the access link as well as relay link in terms of throughput-distance relationship models by using standard channel pathloss model. Utilizing these two throughput-distance models combined throughput-distance model has been developed. Finally the combined throughput-distance relationship model has been used to evaluate the performance of relay-based network.

In performance evaluation of relay-based network, both average throughput and aggregated throughput have been presented as performance metrics and numerical results are compared in case of single-hop, multi-hop and combined coverage scenario. It has been seen that the position of relay has great impact on the performance of relay-based network. Finally, we have shown how to select the coverage and the position of relay to meet the certain service demand while a mobile user traversing the coverage of relay based network.
REFERENCES


