Data Downloading in Relay Assisted Mobile Vehicles

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Abstract—Traditionally, every mobile station (MS) riding in the mobile vehicle uses conventional connection to the base station (BS). However, in 802.16j mobile multihop relay (MMR-BS) networks, one of the studied usage model is “coverage on mobile vehicle”. Therein, a relay station (RS) is mounted on a vehicle. The RS provides service to MSs riding on the vehicle by relaying their data to the mobile multihop relay base station (MMR-BS). This brings several benefits compared to the situation where every MS would individually connect to the MMR-BS, including power savings and better channel condition. In this work, we consider a scenario where user is considered sitting in the vehicle and downloading data via relay station which is mounted on top the vehicle. The downloading typically uses the RS mounted on the vehicle but direct communication to the MMR-BS is also allowed. We characterize both the access links (MS-RS, MS-BS) and the relay link (RS-BS) by throughput-distance relationship models. The decision whether to use RS or to communicate directly with the MMR-BS is decided based on comparing the combined throughput distance model. (MS-RS-BS) with the throughput obtained using direct access link. Numerical results are provided using a two-turn mobility model. The results show that mobility and velocity of mobile vehicle have a great impact on the performance of mobile vehicle relay assisted network.

I. INTRODUCTION

Wireless connectivity on mobile vehicle by relay station (RS) is emerging as an important mode of communication in future wireless communication systems [1]. In this paradigm of wireless communication RS can serve network access on vehicles for stationary terminal inside the mobile vehicle. As a result, 802.16j has considered coverage on mobile vehicle usage model as one of its four usage models [2], [3]. In this usage model, mobile relay RS is mounted on the vehicle and it connects to the mobile multihop relay base station (MMR-BS) via mobile relay link. Sometimes this application of scenario where mobile relays serving stationary terminals is called moving network hence mobile relays are network elements and are expected to be part of future wireless communication networks [4], [5]. Potential benefits of using mobile relays are multiplexing gain, saving battery power of the mobile terminal (MT) and better channel condition because of external antenna of mobile RS [2]. There will be other various applications as well of relay based network which will provide services to passenger hand-held devices, vehicle sensors, actuators, and controllers to access heterogeneous wireless networks while the vehicle is in motion [6]. In this work, we consider a scenario where user is considered sitting in the moving mobile vehicle and downloading data via RS mounted on the mobile vehicle.

However giving benefits of data downloading in mobile vehicle therein significant key challenges in deployment of such relay based wireless networks. RS is network element and due to the mobility of network element, mobile relaying concept is more complex approach in compare to fixed relaying [4]. Network Mobility (NEMO) Basic Support is standardized for moving/mobile networks by extending Mobile IPv6 [6]. This will enable network mobility and wireless connectivity while element of network move [4], [5], [6]. To our best knowledge very few papers have been addressed this usage model described in 802.16j and evaluate the performance of relay based mobile network. In [7], performance evaluation of fixed relay based cellular system has been studied. In [4], [5], solution for power control and allocation has been analyzed for mobile relays. In contrast to the other works, we consider to evaluate the performance of mobile relay network while the user sitting inside the mobile vehicle and download data.

In many cases throughput is considered as the performance metric in performance prediction model to evaluate the performance of wireless network [8]. 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 [7]. On the other hand, performance of mobile relay assisted network depends also on the link budget evaluation for access link and relay link as well as positions of mobile relay from the MMR-BS [8]. Hence, considering the effects of all above mentioned parameters to the throughput, each link may be described as simplified throughput-distance model [7]. 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.

II. MATHEMATICAL FRAMEWORK

Two co-centric circles are used to represent the different segments of traveling path of a mobile vehicle. The outer tier is 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. 1. In the outer tier, stationary user in the mobile vehicle connect to MMR-BS via
mobile RS. On the other hand, in the inner tier the stationary user will connect the MMR-BS without RS. The coverage range of the first tier, and the second tier are $R_{\text{max}}$, and $r_{\text{max}}$ respectively. $R_{\text{max}}$ is the maximum cell range of the combined coverage.

In this work, we have considered two-turn mobility model, the details of two-turn mobility model will be discussed in next Section. In two turn mobility model three segments of traveling distance are created. Two of them are horizontal segments and one of them is vertical segment. For example, the first segment of traveling distance is created by entrance point and one of them is vertical segment. For example, the traveling distance are created. Two of them are horizontal respectively.

The received average throughput of mobile user crossing the coverage of relay-enhanced cell is then given by

$$S_{\text{av}}(r) = \frac{1}{d_1} \int_A^B S(r) \, dr,$$  \hspace{1cm} (7)

where $S(r)$ represents the throughput-distance relationship and $r$ is function of $x$ and $y$. The integral given in (7) is a line integral to calculate the instantaneous throughput along the traveling distance. We can parameterized the location of the mobile vehicle as $(x_c(t-1), y_c(t))$, where $x(t) = x_c(t-1), y(t) = y_c$ and $0 \leq t \leq 1$.

The instantaneous distance $r$ between the center of combined coverage and mobile vehicle can be calculated as

$$r = \sqrt{(x_0 + t(x_c-x_0))^2 + (y_0 + t(y_c-y_0))^2},$$  \hspace{1cm} (8)

where $x_0$ and $x_c$ are initial and final points of a particular segment of line in respective tier. For example, substituting (8) in (7), the average throughput in parameterized form can be expressed as

$$S_{\text{av}}(r) = \int_0^1 S(\sqrt{x_0 + t(x_c-x_0))^2 + (y_0 + t(y_c-y_0))^2}) \, dt.$$  \hspace{1cm} (9)

III. TWO TURN MOBILITY MODEL

In two-turn mobility model, the mobile vehicle will have four different possible turning points during its journey. The turning points ( first turn and second turn) may occur in the outer circle or both turning points may occur in the inner circle. On the other hand, first turning point may reside in the outer circle and second turning point may reside in the inner circle or vice versa. The perceived throughput will depend on the different turns of the mobile vehicle. The calculation of average throughput and aggregated throughput of different turning points are as follows:

A. Both first turn and second turn in multihop region

If both turning points reside inside the multihop coverage as shown in Figure 3a, in that case the average throughput in the first segment and the last segment can be expressed as

$$S_{\text{av}}(r) = \int_0^1 S(\sqrt{x_0 + t(x_c-x_0))^2 + (y_0 + t(y_c-y_0))^2}) \, dt,$$  \hspace{1cm} (10)

where $x_0$ and $x_c$ represent the $x$ component of initial and final point of the respective segmented line and $y_c$ represents the $y$ component. It also represents the minimum distance which has been calculated in (3) and (4) for first and third segments.
The \( x \) component of initial and final points in first segment line can be expressed as

\[
x_0 = x_1^1 = 0
\] (11)
\[
d_1 = x_c = x_1^1 = R_{\text{max}} \sin(\theta_1)
\] (12)

Similarly Equation (10) can be used to calculate the average throughput in third segment where the initial and final point in third segment line can be expressed as

\[
x_0 = x_3^3 = 0
\] (13)
\[
d_2 = x_c = x_3^3 = R_{\text{max}} \sin(\theta_2)
\] (14)

The average throughput in second segment (between two turning points) can be calculated as

\[
S_w(r) = \frac{1}{|y_{c2} - y_{c1}|} \int_A^B S(r) dr,
\] (15)

where \( S(r) \) represents the throughput-distance relationship, \( y_{c1} \) and \( y_{c2} \) represent minimum distances of first and third segment, \( |y_{c2} - y_{c1}| \) is the traveling distance between two turning points and \( r \) is function of \( y \) only. In (15), \( A \) and \( B \) represent the position of first turning and second turning point respectively.

### B. Both first turn and second turn in singlehop region

If both turning points reside inside the singlehop coverage. The calculation of average throughput between entering point and first turning point is two folds. The traveling distance is covered by both multihop and singlehop communications. Therefore, average throughput calculation over subsegments of both first and third segment are calculated as

\[
S_w = \begin{cases} 
\int_0^1 S(\sqrt{(x_0^1 + t(x_1^1 - x_0^1))^2 + y_c^2}) dt, \\
\int_0^1 S(\sqrt{(x_0^1 + t(x_1^1 - x_0^1))^2 + y_c^2}) dt,
\end{cases}
\] (16)

where upper part in (16) is the first subsegment of segment1 and lower part is the second subsegment of segment1. Putting value of initial and final point of \( x \) component and \( y = y_{c1} \) in (16) the segment specific average throughput can be calculated. The initial and final points of first subsegment of segment1 are as follows:

\[
x_c = x_1^1 = R_{\text{max}} \sin(\theta_1).
\] (17)
\[
x_0 = x_{11} = \sqrt{(r_{\text{max}}^2 - y_{c1}^2)}.
\] (18)

The initial and final points of second subsegment of segment1 can be expressed as

\[
x_0 = x_{12} = \sqrt{(r_{\text{max}}^2 - y_{c1}^2)}
\] (19)
\[
x_c = x_{12}^f = 0
\] (20)

Similarly, the initial and final points of two subsegments’s \( x \) component of segment3 can be expressed as

\[
x_0 = x_3^{31} = 0
\] (21)
\[
x_c = x_{31} = \sqrt{(r_{\text{max}}^2 - y_{c2}^2)}
\] (22)

The initial and final points of segment \( 3 \) can be expressed as

\[
x_0 = x_{32} = \sqrt{(r_{\text{max}}^2 - y_{c2}^2)},
\] (23)
\[
x_c = x_{32}^f = R_{\text{max}} \sin(\theta_2),
\] (24)

where \( y_{c2} \) is the minimum distance of segment3. The average throughput between first turn and second turn can be calculated as follows:

\[
S_w(r) = \frac{1}{|y_{c2} - y_{c1}|} \int_A^B S(r) dr,
\] (25)

where \( S(r) \) represents the throughput-distance relationship and \( r \) is function of \( y \) only. \( A \) and \( B \) represent the position of first turning and second turning point respectively.

### C. First turn in multihop and second turn in singlehop region

If first turn in multihop coverage and second turn in singlehop coverage in that case the average throughput in the first segment can be calculated as in Subsection A. On the other hand, throughput in third segment can be calculated as in Subsection B. Finally the average throughput between first turn and second turn can be calculated as

\[
S_w = \begin{cases} 
\int_{r_{\text{max}} < y_c1 < R_{\text{max}}} \frac{1}{|y_{c2} - y_{c1}|} \int_A^B S(r) dr, \\
\int_{y_{c2} < y_c1 < R_{\text{max}}} \frac{1}{|y_{c2} - y_{c1}|} \int_A^B S(r) dr,
\end{cases}
\] (26)

### D. First turn in singlehop and second turn in multihop region

If first turn in singlehop region and second turn in multihop region, the average throughput in the first segment can be calculated as it is calculated in Subsection B. The average throughput in third segment can be calculated as it is calculated in Subsection A. The average throughput in second segment can be calculated as

\[
S_w = \begin{cases} 
\int \frac{1}{|y_{c2} - y_{c1}|} \int_A^B S(r) dr, 0 < y_c1 < R_{\text{max}}, \\
\int \frac{1}{|y_{c2} - y_{c1}|} \int_A^B S(r) dr, r_{\text{max}} < y_c2 < R_{\text{max}},
\end{cases}
\] (27)

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) \( t_{\text{dwell}} \) is given by

\[
I_t = S_{\text{total}} t_{\text{dwell}},
\] (28)

where \( S_{\text{total}} \) 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 vehicle. The relationship between traveling distance, dwelling time and velocity \( v \) can be expressed as

\[
t_{\text{dwell}} = \frac{d_1 + |y_{c2} - y_{c1}| + d_2}{v},
\] (29)

where \( v \) is the velocity of mobile vehicle and expressed in m/s.
IV. USAGE AND CHANNEL MODEL

In standard [8], 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 RS with good Line of Sight (LOS) back to the MMR-BS. The LOS pathloss model for relay link can be expressed as

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

where \(r_1\) is the distance in meter between MMR-BS and RS. On the other hand, for the access link, we have chosen Non-Line-of-Sight (NLOS) channel model, whose pathloss can be characterized as

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

where \(r_2\) is the distance between MMR-BS and MT in meter, \(h_m\) is the antenna height of RS. 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 (30) can be expressed as

$$d_{\text{switch-}\text{a}} = 10^{\frac{r_2(N_{\text{dB}})+25.5-N[N_{\text{dB}}]-SNR[\text{dB}]}{10}},$$

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 [9]

$$N = BW \cdot 4 \cdot 10^{-12},$$

where \(BW\) is the bandwidth of the system. Similarly in case of access link, the switching distance between different modulation techniques can be expressed as

$$d_{\text{switch-}\text{al}} = 10^{\frac{r_2(N_{\text{dB}})+25.5-N[N_{\text{dB}}]-SNR[\text{dB}]-0.7h_m[m]}{10}},$$

A. Throughput-distance Model

In this work, throughput-distance relationship is modeled by calculating the rate adaptive switching distance as given in (30) and (34) and then mapping this effective distance to a throughput as outlined in Table I [10]. The approximated linear throughput-distance relationship for relay link (MMR-BS——>RS) can be expressed as

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

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

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

where \(r_{\text{max}}\) is the maximum cell range in access link. By using (35) and (36) combined throughput distance relationship has been created. The combined throughput distance relationship

is shown in Fig. 2. Combined throughput distance relationship model can be expressed as

$$S(r) = \begin{cases} a_1 r + b_1, & 0 < r < x_s \\ a_2 r + b_2, & x_s < r < R_{\text{max}} \end{cases},$$

where \(a_1\) and \(b_1\) in (37) can be expressed as

$$a_1 = \frac{(71 - y_s)}{x_s},$$

$$b_1 = 71.$$

Similarly \(a_2\), \(b_2\) and \(b_3\) in (37) can be expressed as

$$a_2 = \frac{y_s}{(x_s - R)},$$

$$b_2 = 32.40.$$  

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

$$s_{\text{seg}} = a_i(\ln(x_e + \sqrt{x_e^2 + y_c^2})) + x_c \sqrt{x_e^2 + y_c^2} - x_0 \sqrt{x_e^2 + y_c^2} + \frac{y_c}{2(x_e - x_0)} + b_i,$$

where \(x_0\), \(x_f\) and \(y_c\) are calculated in Section 3 and the values of \(a_1\) and \(b_1\) are segment specific as calculated in above equations.

The total average throughput the user can download while mobile vehicle traverses both single-hop and multi-hop communication can be represented as

$$S_{\text{total}} = S_1 d_3 + S_2 d_2 + S_1 d_1,$$

where \(S_1\), \(S_2\), \(S_3\) are the average throughputs in segment 1 and segment 2 and segment 3 respectively.
V. NUMERICAL RESULTS AND DISCUSSION

Path-average throughput probability density function (PDF) and cumulative distribution function (CDF) of the data downloaded during single pass are used herein for performance evaluation. Path-average throughput refers to the average throughput of some specific path, from the entrance to the cell to the exit. File size downloaded refers to the amount of data that can be downloaded during single pass of the cell from entrance to the exit.

Fig. 3. Average throughputs.

Fig. 3 shows the distribution of path-average throughputs over large number of different path realizations. It can be seen that the path-average PDF has peak at around 13 Mbps. However, the average occurs at 9.2 Mbps. Also it can be seen that there are paths where the path-average throughput is quite small like 1 Mbps. The variation between paths is very large as some path have throughput close to 30 Mbps.

Fig. 4. File Size at different velocities.

Fig. 4 shows the file size of downloaded data of the stationary user sitting in the mobile vehicle. It is seen that at 80 percent success rate the user can download up to 208.7 MByte of data at 30 km/h. On the other hand, with this low speed (30 km/h), at 50 percent of success rate the user can download higher amount of data which is 760 Mbyte. The numerical results also show that with same success rate the stationary user can download half of the amount of data even when the speed limit of the vehicle is increased from 30 km/h to 60 km/h. The reason is when the velocity of mobile vehicle increases, the dwelling time of the user in the coverage decreases.

VI. CONCLUSION

In this work, we develop a methodology to evaluate the performance of coverage on mobile vehicle usage model scenario proposed in 802.16j. The main objective is to investigate the success rate of the service demand of stationary user who is sitting in mobile vehicle and downloading data under various conditions such as mobility model of the vehicle and residence of the user either in singlehop or multihop coverage. 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 mobile vehicle relay assisted network.

REFERENCES