CrossMark

Relay Multi-hop Communications for Next Generation Mobile Networks: Investigation of Path-Loss Models

Huseyin Aniktar[1] · Umut Bulus[1]

Abstract In next generation communication systems, a multi-hop scheme, in which stations between a mobile terminal and a base station relay signal transmissions, seems a promising ap-proach for wide-area coverage and system capacity enhancement. Another prospective benefit for multi-hop scheme is the reduction of transmission power for a link. This reduction is expected by splitting the transmission into a series of hops using the other mobile stations as repeaters which provide a gain from receiver (Rx) to transmitter (Tx). In this way, the transmission power is expected to become less due to the non-linear nature of the path loss. In this work, different path loss models are examined for multi-hop communication systems. Direct communication and the multi-hop communication cases are compared according to different path loss models. The question of how path loss changes by splitting the transmission into a series of sub-paths is also investigated. The investigations show that it is not possible to reduce the path losses except for some cases thus the transmit power. On the other hand using the multi-hop scheme makes possible to increase the coverage area of the network and also reduce the dead spots in the cell.

Keywords Multi-hop networks · Propagation models · Path-loss · Next generation mobile networks

✉ Huseyin Aniktar
  huseyin.aniktar@tubitak.gov.tr

  Umut Bulus
  umutbulus@yahoo.com

[1] TUBITAK-BILGEM, P.O. 74, 41470 Gebze, Kocaeli, Turkey

1 Introduction

In recent years, the rapid increase in data-traffic consumption by cellular users will require to implement new connectivity schemes that guarantee acceptable levels of Quality of Service (QoS) and reliability. Multi-hop relaying in next generation cellular networking, with and without the direct intervention of the infrastructure, is foreseen to revolutionize the way connections will be established, combining the traditional centralized schemes of connectivity (where users connect exclusively through their nearest Base Station, or at most from a fixed relay station), with the new paradigm of Device-to-Device (D2D) networking (in which users are allowed to communicate peer-to-peer through direct links that do not necessarily involve the intervention of a Base Station). According to several research studies, the benefits of this new approach are numerous: higher spectrum efficiency, better fairness in resource allocation, energy efficient usage, among others. However, this novel approach for wireless cellular networking faces the challenge of distributed management of communications, subject to mobility, in which end-user terminals will play a more active role in the self-configuration of the network [1–3].

In multi-hop cellular networks (MCN), communication is not established directly between the user equipment (UE) and the base station (BS) [4–7]. Instead, intermediate devices act as repeaters between the BS and a UE. In this way, it is expected to decrease the total required transmission power and possibly mitigate interference and coverage problems and also it is expected to provide service in 'dead spots' in a cell, which are not reachable by the BS in direct communication case.

In this paper, by using different path loss models between the mobile (UE or repeater) and base station terminals, the question of how path loss changes by splitting the transmission into a series of sub-paths is investigated. To procure this, first, these path loss models are described. After describing the path loss models, multi-hop and direct communication cases are compared according to these path loss models and finally, some conclusions are drawn.

2 Path Loss Models

In this section, several path loss models are described. These models are (1) the simplest path loss model, (2) COST231-Hata model, (3) Walfisch–Bertoni path loss model, (4) COST231-Walfisch–Ikegami Line-of-Sight model, and (5) Non-Line-of-Sight model. Before describing these models, network cell types are described. The most appropriate propagation prediction technique for a given system is highly dependent on the chosen cell type. Each of the four major cell types is described in this section [7, 8]. Each path loss model is valid for different conditions and cell types. When the path loss models are described, the restrictions of the each model are also expressed.

2.1 Cell types

Different cell types and their restrictions are investigated in this section.

2.1.1 Macro-Cell

In the macro-cell, typical cell radius is about 1–30 km. The BS antenna is mounted above the roof-top level and the heights of the all surrounding buildings are below the base station antenna height [8, 9].

2.1.2 Small Macro-Cell

In the small macro-cell, typical cell radius is about 0.5–3 km. The BS antenna is mounted above the medium roof-top level and the heights of the some surrounding buildings are above the BS antenna height [8–10].

2.1.3 Micro-Cell

In the micro-cell, typical cell radius is up to 1 km. The BS antenna is mounted below the medium of the top level [8–10].

2.1.4 Pico-Cell

In the pico-cell, typical cell radius is up to 500 m. The BS antenna is mounted below the roof-top-level [8–10].

Radio propagation loss basically consists of three components. These components are the distance dependent path loss component, shadowing component, and the fast fading component. Shadowing and the fast fading loss components are generally assumed to be independent of the distance, but de-pendent on the local environment such as the arrangement of the streets and buildings [2]. The propagation loss formula can be expressed by Eq. 1 [2]:

$$L = PL + L_S + L_f \text{ in dB} \tag{1}$$

where "PL" is the distance dependent path loss component, "L_S" is the shadowing component, and the "L_f" is the fast fading component. This paper, only focus on the models available for the distance dependent path loss. Fast fading and shadowing effects have not been taken into account. Some path loss models are described as follows.

2.2 Path Loss Models

Different path loss models and their restrictions are investigated in this section.

2.2.1 The Simplest Empirical Path Loss Model

The simplest useful form for an empirical path loss model can be expressed by Eqs. 2 and 3 [8, 11].

$$PL_{dB} = A + 10 \cdot n \cdot \log\left(\frac{d}{d_o}\right) \quad \text{for d} \geq \text{d}_o \tag{2}$$

Table 1 Path loss exponents, n [10]	Environment	Path loss exponent, n
	Free space	2
	Ideal specular reflection	4
	Urban cells	2.7–3.5
	Urban cells, shadowed	3–5
	In building, line-of-sight	1.6–1.8
	In building, obstructed path	4–6
	In factory, obstructed path	2–3

$$A_{dB} = 20 \cdot log\left(\frac{4\pi d_o}{\lambda}\right) \tag{3}$$

where "n" is the path loss exponent, "d" is the distance between the transmitter (Tx) and the receiver (Rx) antennas, in meters, "d_o" is the reference distance and "λ" is the wavelength of the center frequency of the waveform. In this paper, the reference distance (d_o) is taken as 1 m. d_o is often determined empirically. d_o should be selected such that it is in the far-field of the Tx antenna, but still small relative to any practical distance used in the mobile communication system [12]. For n = 2, this formula gives us the special case of free-space path loss. Path loss exponents are listed in Table 1 for different environments.

2.2.2 COST231-Hata Model

COST231-Hata model is the extended version of the Okumura–Hata model to cover the band 1500 MHz $\leq f_c \leq$ 2000 MHz. COST231-Hata model is given by Eqs. 4, 5 and 6 [9].

$$PL_{dB} = 46.3 + 33.9 \cdot \log(f) - 13.82 \cdot \log(h_b) - a(h_m) + (44.9 - 6.55 \cdot \log(h_b))$$
$$\cdot \log\left(\frac{d}{1000}\right) + C_m \tag{4}$$

$$a(h_m) = (1.1 \cdot \log(f) - 0.7) \cdot h_m - 1.56 \cdot \log(f) + 0.8 \tag{5}$$

$$C_m = \begin{cases} 0\,dB, & \text{for medium sized city and suburban centres with medium tree density} \\ 3\,dB, & \text{for metropolitan centres} \end{cases} \tag{6}$$

The COST-Hata model is restricted to the following range of parameters [9]: Operating frequency, f (1500–2000 MHz); base station antenna height, h_b (30–200 m); mobile terminal antenna height, h_m (1–10 m) and the distance, d (1000–2000 m). The application of the COST-Hata model is restricted to large and small macro-cells, i.e. base station antenna heights above the roof-top levels adjacent to the base station. Hata formula and its modification must not be used for micro-cells since the validity of the model is restricted for distance over 1 km [13].

2.2.3 Walfisch–Bertoni Model

The Walfisch–Bertoni path loss model is given by Eqs. 7, 9 and 10 [14].

$$PL_o = 32.4 + 20 \cdot \log(f) + 20 \cdot \log(d/1000) \tag{7}$$

where PL_o is the free space path loss formula, d is the distance in meters, and f is the frequency in MHz.

$$PL_{ex} = 57.1 + A + \log(f) + 18 \cdot \log\left(\frac{d}{1000}\right) - 18 \cdot \log(h_b - h_r) - 18$$
$$\cdot log\left[1 - \frac{(d/1000)^2}{17(h_b - h_r)}\right] \tag{8}$$

where PL_{ex} is the excess path loss. The influence of the building geometry is contained in the term A,

$$A = 5 \cdot log \left[\left(\frac{b}{2} \right)^2 + (h_r - h_m)^2 \right] - 9 \cdot log(b) + 20 \cdot log \left[tan^{-1} \cdot \left(2 \cdot \frac{(h_r - h_m)}{b} \right) \right] \quad (9)$$

h_r is the height of a building in meters, h_m is the mobile terminal antenna height in meters, h_b is the base station antenna height and b is the building separation in meters.

The overall path loss PL is found by adding PL_{ex} to the free space path loss PL_o as Eq. 10.

$$PL_{dB} = PL_o + PL_{ex} \quad (10)$$

The Walfisch–Bertoni model is especially suitable for predicting average path loss in urban environments in the UHF band (300 MHz–3 GHz) [14].

2.2.4 COST231-Walfisch–Ikegami LOS Model

The COST231 Walfisch Ikegami (WI) model allows for improved path loss estimation by consideration of more data to describe the character of the urban environment [9]. The model distinguishes between the line-of-sight (LOS) and the non-line-of-sight (NLOS) situations. The COST231 WI LOS model is given by Eq. 11 [9]:

$$PL_{dB} = 42.6 + 26 \cdot log(d/1000) + 20 \cdot log(f) \quad \text{for d} \geq 20 \text{ m.} \quad (11)$$

where PL is in dB, d is distance in meters and f is frequency in MHz.

2.2.5 COST231-Walfisch–Ikegami NLOS Model

In the NLOS case the basic transmission loss is composed of the terms free space loss L_o, multiple screen diffraction loss L_{msd}, and roof-top-to-street diffraction and scatter loss L_{rts} [9]. The path loss formula for this model is given by Eq. 12 [9].

$$PL_{dB} = \begin{cases} L_o + L_{rts} + L_{msd}, & for \quad L_{rts} + L_{msd} > 0 \\ L_o, & for \, L_{rts} + L_{msd} \leq 0 \end{cases} \quad (12)$$

The free space path loss is given by Eq. 13.

$$L_o = 38.4 + 20 \cdot log(d) \quad (13)$$

L_{rts} is the roof-top-to-street diffraction and scatter loss in dB, and it is given by Eq. 14.

$$L_{rts} = -16.9 - 10 \cdot log(w) + 10 \cdot log(f) + 20 \cdot log(\delta h_m) + L_{ori} \quad (14)$$

L_{ori} is given by Eq. 15,

$$L_{ori} = \begin{cases} -10 + 0.354 \cdot \emptyset & for \quad 0 \leq \emptyset < 35 \\ 2.5 + 0.075 \cdot (\emptyset - 35) & for \quad 35 \leq \emptyset < 55 \\ 4 - 0.114 \cdot (\emptyset - 55) & for \quad 55 \leq \emptyset < 90 \end{cases} \quad (15)$$

where ϕ is the road orientation with respect to the direct radio path in degrees. The L_{msd} is the multiple screen diffraction loss in dB, and it is given by Eq. 16.

$$L_{msd} = L_{bsh} + k_a + k_d \cdot log\left(\frac{d}{1000}\right) + k_f \cdot \log(f) - 9 \cdot \log(b) \tag{16}$$

L_{bsh} is expressed as in Eq. 17, k_a, k_d and k_f are expressed as in Eqs. 18, 19 and 20 respectively.

$$L_{bsh} = \begin{cases} -18. \log(1 + \Delta h_b) & for \quad h_b > h_r \\ 0 & for \quad h_b \leq h_r \end{cases} \tag{17}$$

$$k_a = \begin{cases} 54 & for \quad h_b > h_r \\ 54 - 0.8 \cdot \Delta h_b & for \quad d \geq 500 \text{ m } and \ h_b \leq h_r \\ 54 - 0.8 \cdot \Delta h_b \cdot \dfrac{d}{500} & for \quad d < 500 \text{ m } and \ h_b \leq h_r \end{cases} \tag{18}$$

$$k_d = \begin{cases} 18 & for \quad h_b > h_r \\ 18 - 15. \dfrac{\Delta h_b}{h_r} & for \quad h_b \leq h_r \end{cases} \tag{19}$$

$$k_f = -4$$
$$+ \begin{cases} 0.7. \left(\dfrac{f}{925} - 1\right) & for\ medium\ sized\ city\ and\ suburban\ centres\ with\ medium\ tree\ density \\ 1.5. \left(\dfrac{f}{925} - 1\right) & for\ metropolitan\ centres \end{cases}$$
$$\tag{20}$$

Δh_m and Δh_b are expressed as in Eqs. 21 and 22 respectively.

$$\Delta h_m = h_r - h_m \tag{21}$$

$$\Delta h_b = h_b - h_r \tag{22}$$

h_b is the base station antenna height in meters, h_r is the height of a building in meters, h_m is the mobile station antenna height in meters, d is the distance in meters, f is the center frequency of the carrier in MHz, w is the widths of the roads in meters and b is the building separation in meters. The COST-WI model is restricted to [9]; f (800–2000 MHz), h_b (4–50 m), h_m (1–3 m) and d (20–5000 m).
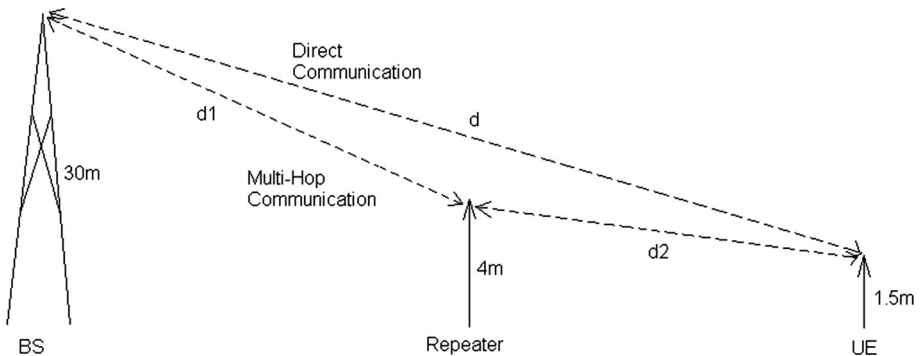

Fig. 1 Direct communication and multi-hop communication with one hop

3 Simulations

In this section, direct communication and multi-hop communication performances are compared. In the multi-hop communication case, one hop (one repeater) is used. It is assumed that the repeater is in the mid point of the BS and the UE. Multi-hop and direct communication cases are depicted in Fig. 1. In Figs. 2 and 3, equivalent block diagrams are depicted for direct communication and multi-hop communication cases respectively.

In Fig. 2, P_r is the BS received power, P_t is the UE transmit power, G_r is the receive antenna gain, G_t is the transmit antenna gain and L is the propagation loss. In Fig. 3, P_{r2} is the BS received power, P_{t1} is the repeated UE transmit power, G_{t1} is the repeated UE transmit antenna gain, G_{r1} is the repeater receive antenna gain, G is the repeater gain, G_{t2} is the repeater transmit antenna gain, P_{r2} is the BS receive antenna gain, L1 and L2 are propagation losses.

The link equation for Fig. 2 is expressed as in Eq. 23.

$$10 \cdot log(P_r) = 10 \cdot log(P_t) + 10 \cdot log(G_t) + 10 \cdot log(G_r) - 10 \cdot \log(L) \qquad (23)$$

The link equation for Fig. 3 is expressed as in Eq. 24.

$$10 \cdot \log(P_{r2}) = 10 \cdot \log(P_{t1}) + 10 \cdot \log(G_{t1}) + 10 \cdot \log(G_{r1}) + 10 \cdot \log(G) + 10 \cdot log(G_{t2})$$
$$+ 10 \cdot log(G_{r2}) - 10 \cdot log(L_1) - 10 \cdot log(L_2)$$

$$(24)$$

The simulations are based on the comparison between the 10·log(L) (direct communication case) and 10·log(L1) + 10·log(L2) (multi-hop communication case). For this comparison, three different scenarios are drawn. In each scenario, different path loss models are applied between the BS and the UE, BS and the Repeater, and the Repeater and the UE. These path loss models are compared according to different distances. The parameters which are used in simulation are given in Table 2.

Scenarios are drawn according to three different cases;

1. Between a BS and a UE.
2. Between a BS and a repeater.
3. Between a repeater and a UE.

For each case different path loss models and environment conditions are applied. Multi-hop and direct communication system performances are compared based on the following scenarios.
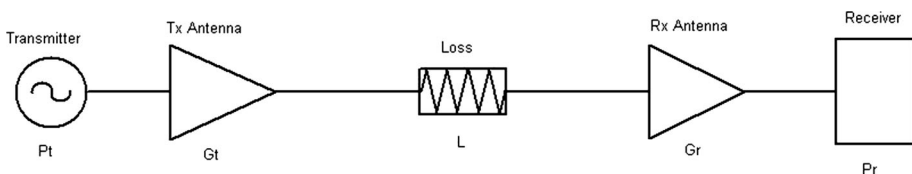

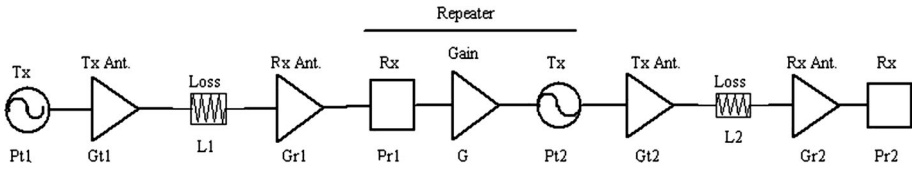**Fig. 2** Direct communication equivalent block diagram

Fig. 3 Multi-hop communication equivalent block diagram for one hop

Table 2 Propagation parameters for simulation [9, 15]

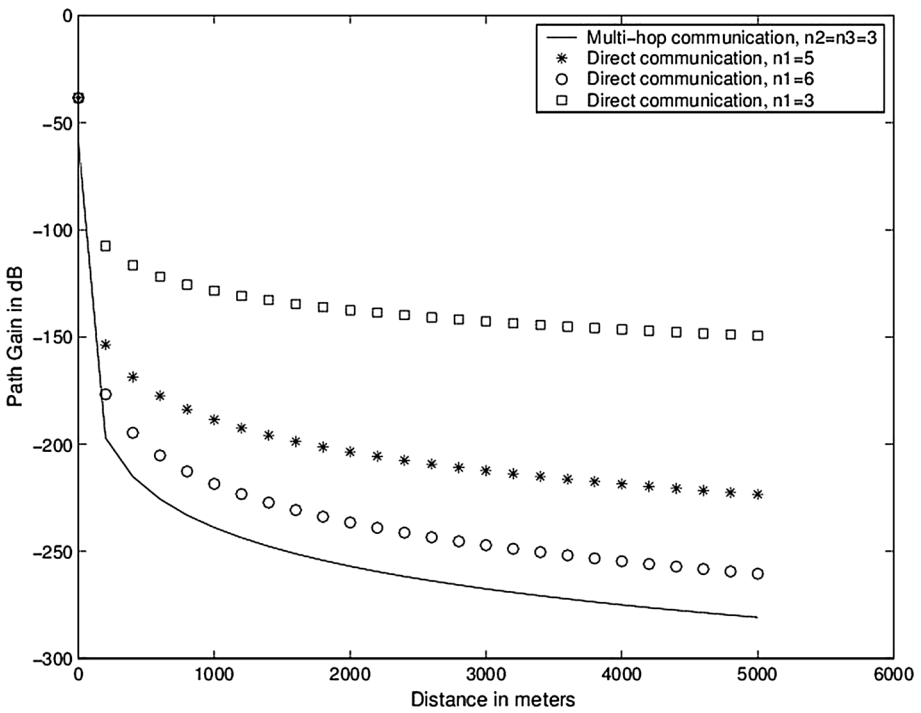| Parameter	Value
Frequency	2000 MHz
Repeater antenna height	4 m
UE antenna height	1.5 m
Height of buildings	15 m
Width of roads	15 m
Building separation	90 m
Street orientation with respect to direct path	90°
Base station antenna height	30 m

Fig. 4 Direct communication and multi-hop communication performance comparison for scenario I

3.1 Scenario I

In scenario I, the simplest path loss model is applied to all cases. Different path loss exponents are used for cases (1), (2) and (3). Simulation results are depicted in Figs. 4 and 5.

In all figures, path gain term is used instead of the path loss term ("Path Gain = −Path Loss", both in dB). In figures, 'n1' indicates the path loss exponent for direct communication case, 'n2' and 'n3' indicate the path loss exponents for multi-hop communication case between the BS-Repeater and the Repeater-UE respectively.

In Fig. 4, square dotted line, star dotted line and circle dotted line show the direct communication case with path loss exponents 3, 5 and 6, respectively. Solid line shows the multi-hop communication case. In the multi-hop communication case, the path loss exponent is used as 3 for both BS-Repeater and Repeater-UE. As can be seen in Fig. 4, the path gain in multi-hop communication case is lower than the direct communication case. If the path loss exponent is 7 or more than this, then the path gain for the multi-hop communication case is lower than the direct communication case. But this is also a non realistic situation.

In Fig. 5, star dotted line, circle dotted line, and square dotted line show the direct communication case with path loss exponents 4, 5 and 6, respectively. Solid line shows the multi-hop communication case with the path loss exponent 2 for both BS-Repeater and Repeater-UE. As seen in Fig. 5, if the path loss exponent is larger than the about five for the direct communication case, the multi-hop com-munication performance is better than
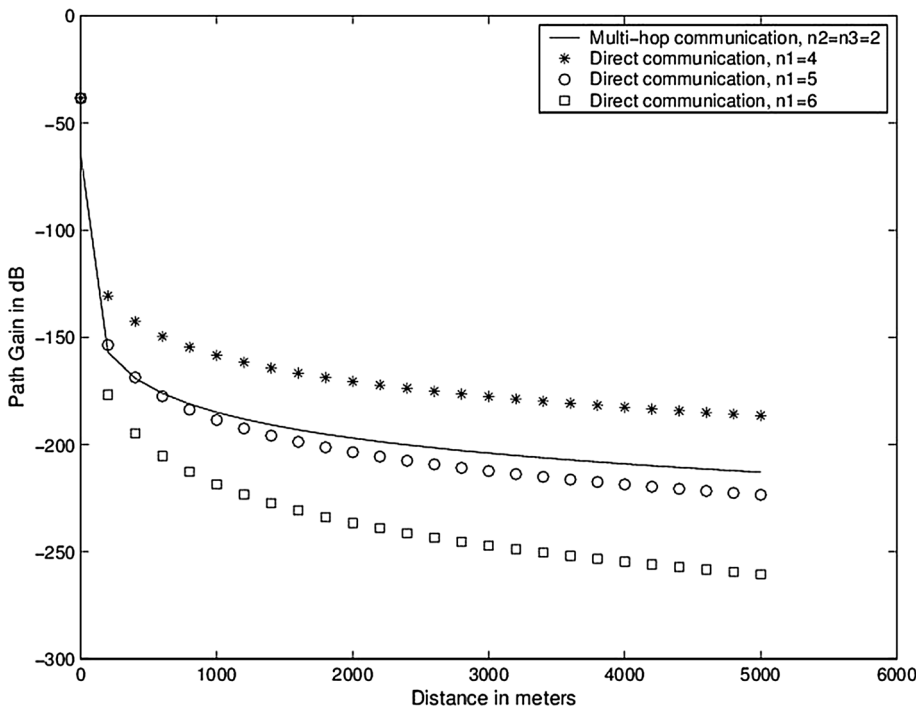

Fig. 5 Direct communication and multi-hop communication performance comparison for scenario I

the direct communication case. According to simulation results, when the path loss exponent in the multi-hop communication case is much smaller than in the direct communication case, then we can expect better performance for the multi-hop communication system.

For the direct communication case, the path loss is formulated as in Eq. 25.

$$PL1 = 20 \cdot log\left(\frac{4\pi d_o}{\lambda}\right) + 10 \cdot n_1 \cdot log\left(\frac{d}{d_o}\right) \tag{25}$$

For the multi-hop communication case with one hop, the path loss is formulated as in Eq. 26.

$$PL2 = 40 \cdot log\left(\frac{4\pi d_o}{\lambda}\right) + 10 \cdot n_2 \cdot log\left(\frac{d_1}{d_o}\right) + 10 \cdot n_3 \cdot log\left(\frac{d_2}{d_o}\right) \tag{26}$$

To get lower propagation loss in the multi-hop communication case than in the direct communication case, the Eq. 27 should hold.

$$PL2 < PL1 \tag{27}$$

After some mathematical operations, the Eqs. 28 or 29 can be found.
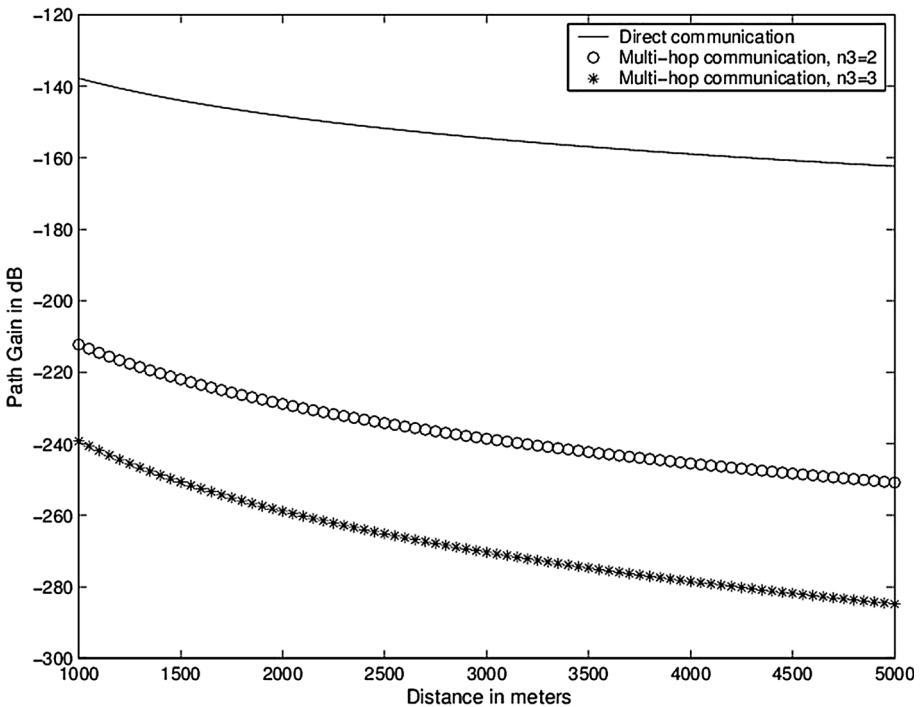

Fig. 6 Direct communication and the multi-hop communication performance comparison for scenario II

$$\log\left[\left(\frac{4\pi d_o}{\lambda}\right)^2 \cdot \left(\frac{d_1}{d_o}\right)^{n_2} \cdot \left(\frac{d_2}{d_o}\right)^{n_3} \cdot \left(\frac{d_o}{d}\right)^{n_1}\right] < 0 \tag{28}$$

or

$$\left(\frac{d_1}{d_o}\right)^{n_2} \cdot \left(\frac{d_2}{d_o}\right)^{n_3} \cdot \left(\frac{d_o}{d}\right)^{n_1} < \left(\frac{\lambda}{4\pi d_o}\right)^2 \tag{29}$$

If the path loss exponent n_1 is large enough in the direct communication case because of the bad environment condition, then if we choose the optimum repeater position such away that the path loss exponents n_2 and n_3 are very low and d_1 and d_2 distances are optimum so the above equation holds, then we can expect the some path loss reductions in multi-hop communication case according to the direct communication case. The important issue here is to estimate the path loss exponents between the terminals and to determine the optimum number of repeaters and the distances between them.

3.2 Scenario II

In scenario II, the proposed propagation models for multi-hop communication and the direct communication systems are: For case (1) and case (2), the COST-Hata model is used. For case (3), the simplest path loss model is used for different path loss exponents. In Fig. 6, comparison between the direct communication and the multi-hop communication is shown.
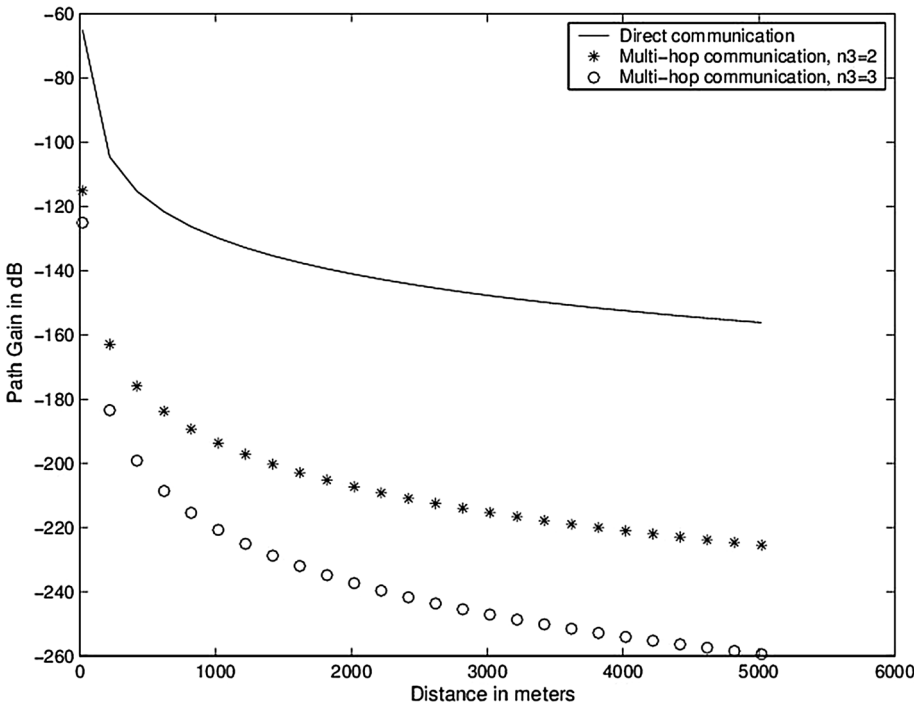

Fig. 7 Direct communication and the multi-hop communication performance comparison for scenario III

3.3 Scenario III

In scenario III, the proposed propagation models for multi-hop communication and the direct communication systems are: For case (1), the COST-WI-NLOS model is used. For case (2), the COST-WI-LOS model is used and for case (3), the simplest path loss model is used for different path loss exponents. In Fig. 7, comparison between the direct communication and the multi-hop communication is shown.

3.4 Scenario IV

In scenario IV, the proposed propagation models for multi-hop communication and the direct communication systems are: For case (1) and (2), the Walfisch Bertoni model is used. For case (3), the simplest path loss model is used for different path loss exponents. In Fig. 8, comparison between the direct communication and the multi-hop communication is shown.

Based on Figs. 6, 7 and 8, it might be never possible to reduce the total transmit power in the multi-hop communication system according to scenario II, III and IV. To decrease the total transmit power, by splitting a communication path into two parts, large increases in the path gains are needed, and these might be difficult to come by in these scenarios. Path gain curves are going to be almost flat after the about 1 km distance. If the path loss exponent changes drastically between the BS and the UE because of the different environment conditions, in this case it is possible to expect the big path loss changes between
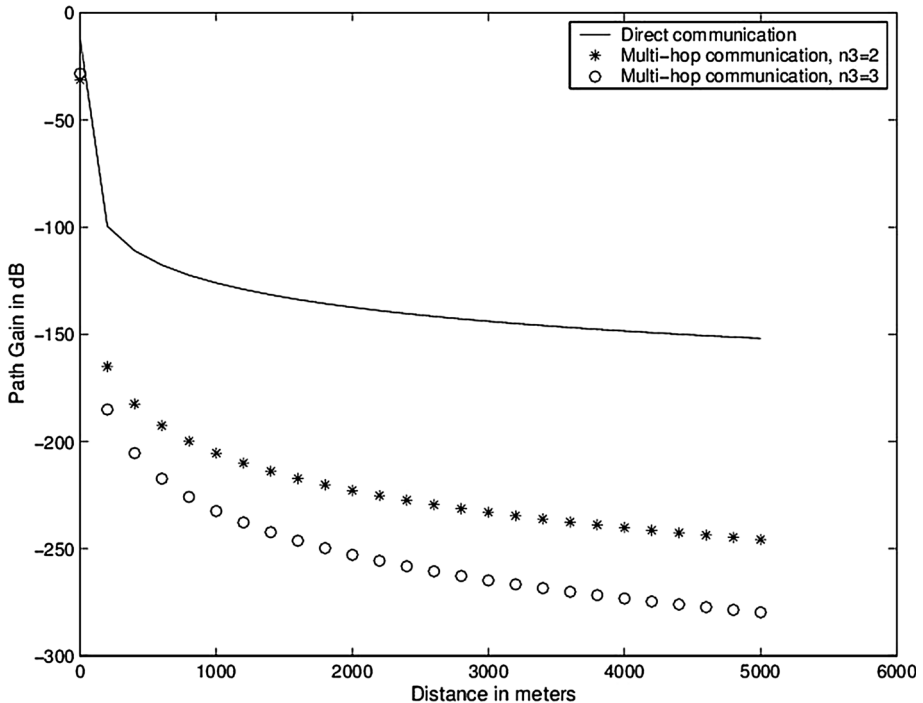

Fig. 8 Direct communication and the multi-hop communication performance comparison for scenario IV

the BS and the UE. In such a case, splitting the path between the BS and the UE into a number of hops allows to reduce the path loss.

Most propagation models assume that the transmit antenna is high and the receive antenna is low. However, the repeater and the UE antennas are low placed antennas. This also shows that it is needed more elaborated path loss models for multi-hop communication systems, especially between the repeater and the UE.

4 Conclusions

In this paper, multi-hop and direct communication cases are compared by using the different scenarios. According to comparisons, in some cases it is possible to reduce the path losses by using the multi-hop communication but generally it is not possible to reduce the path losses. To reduce the path loss between the BS and the UE by using the multi-hop communication system, large changes (reductions) in the path loss between the BS and the UE are needed.

For multi-hop communication, to investigate the more accurate path loss models is one of the important issues. The other important issue in multi-hop communication systems is to define the optimum number of repeaters and the optimum distances. This will also affect the multi-hop system performance.

By using the multi-hop communication, almost each individual mobile terminal' transmit power reduces even though total transmit power increases except for some cases. Reduction in the transmit power of the each individual mobile terminal gives the opportunity to reduce the interference problems and perhaps also reduce the potential health risk. In the multi-hop communication system, using the some user equipments as repeaters will increase the coverage area of the network and also reduce the dead spots in the cell. These benefits of the multi-hop communication systems are also important even though it is not possible to reduce the path losses except for some cases. Yet another issue is that the repeater gain between Rx and Tx has not been included. This gain helps on the performance of multi-hop networks.

Multi-hop communication systems hold promise for next generation mobile systems. However, multi-hop systems need to overcome some challenging topics. To develop an accurate and more elaborated path loss model and to develop optimum routing algorithms are some of them.

References

1. Shah, R., Tuan, T., Sheets, M., Rabaey, J. M., Nikolic, B., Sangiovanni-Vincentelli, A., & Wright, P. (2001). Design Methodology for PicoRadio Networks. In *Proceedings of design automation and test in europe (DATE)*, pp. 314–325.
2. Yamao, Y., Fujiwara, A., Murata, H., & Yoshida, S. (2002). Multi-hop radio access cellular concept for fourth-generation mobile communications system. In *The 13th IEEE international symposium on PIMRC*.
3. Lauridsen, M., Berardinelli, G., Sorensen, T. B., & Mogensen, P. E. (2014). Ensuring energy efficient 5G user equipment by technology evolution and reuse. In *The 79th IEEE vehicular technology conference*.
4. Muqattash, A., Krunz, M., & Ryan, W. E. (2003). Solving the near–far problem in CDMA-based Ad Hoc networks. *Ad Hoc Networks Journal, 1*, 435–453.

5. Kumar, K. J., Manoj, B. S., & Murthy, C. S. R. (2002). On the use of multiple hops in next generation cellular architectures. In *Proceedings of IEEE international conference on networks (ICON)*, pp. 283–288. Singapore.

6. Fujiwara, A., Takeda, S. & Yoshino, H. & Otsu, T. (2002). Area coverage and capacity enhancement by multihop connection of CDMA cellular network. In *Proceedings of IEEE vehicular technology conference*, pp. 2371–2374. Fall.

7. Karlsson, R. S., Aniktar, H., Mikkelsen, J. H., & Larsen T. (2005). Performance of a WCDMA FDD cellular multihop network. In *The 13th IEEE international symposium on PIMRC*.

8. Fujimoto, K., & James, J. (2001). *Mobile antenna systems handbook* (2nd ed.). Norwood, MA: Artech House, Inc.

9. COST231 working group. (1991). Urban transmission loss models for mobile radio in the 900- and 1800-MHz bands. *COST231, TD(973)119-REV(WG2)*.

10. Arnbak, J. (1993). *Mobile radio propagation lecture note*. Delft, The Netherlands: Delft University of Technology.

11. Chang, K. (2000). *RF and microwave wireless systems*. New York: Wiley, Inc.

12. Rappaport, T. (2002). *Wireless communications: principles and practice* (2nd ed.). Upper Saddle River, NJ: Prentice Hall.

13. Hata, M. (1980). Empirical formula for propagation loss in land mobile radio services. In *IEEE transaction on vehicular technology*, pp. 317–325.

14. Walfisch, J., & Bertoni, H. L. (1988). A theoretical model of UHF propagation in urban environments. *IEEE Transactions on Antennas and Propagation, 36*, 1788–1796.

15. 3GPP. (2003). Radio frequency system scenarios. *3GPP technical report. TR 25.942 v6.1.0*.

Hüseyin Aniktar (M'12) was born in Istanbul, Turkey, in 1977. He received the B.Eng. degree in electronic engineering from the Istanbul Technical University, in 1998, the M.Sc. degree in electrical and electronics engineering from the Middle East Technical University, Ankara, Turkey, in 2001, and the Ph.D. degree in RF Integrated Circuits from the Aalborg University, Denmark, in 2007. He has senior RF design engineer position at TUBITAK-BILGEM, Kocaeli, Turkey for 7 years. His research interests cover the design and analysis of RF circuits and systems.

Umut Bulus, Msc.-Eng received Bachelor degree in Electronics and Telecommunication Engineering from Istanbul Technical University in 2005 and Master degree from Duisburg-Essen University in 2008. He worked in IMST Gmbh and Fraunhofer Institute in Germany during 2006 and 2008. He worked as Antenna Design Engineer in Electromagnetics and Antennas Research Group at TUBITAK, Turkey during 2008 and 2013. He is currently in Meteksan Defence as RF system engineer. His scientific interests concern design and measurement of Antennas & Microwave Structures.