Wireless Pers Commun (2010) 53:349–364
DOI 10.1007/s11277-010-9951-5

Cooperative Communications in Future Home Networks

Zülküf Genç · Umar H. Rizvi · Ertan Onur · Ignas Niemegeers

Published online: 16 March 2010

Abstract The basic idea behind cooperative communications is that mobile terminals collaborate to send data to each other. This effectively adds diversity in the system and improves the overall performance. In this paper, we investigate the potential gains of cooperative communication in future home networks. We derive analytical expressions for the error probability of binary phase shift keying (BPSK) signals over Nakagami-*m* fading channels in a multi relay communication network. Following to the analytical study, we analyze the contribution of cooperative relaying to the 60 GHz network connectivity through simulations using a realistic indoor environment model. We compare the performance of different relay configurations under variable obstacle densities. We show that a typical 60 GHz indoor network should employ either a multi-relay configuration or a single-relay configuration with a smart relay selection mechanism to achieve acceptable outage rates. In the use of multiple-relay configuration, both analytical and simulation studies indicate that increasing the number of cooperative relays does not improve the system performance significantly after a certain threshold.

Keywords 60 GHz · Connectivity · Cooperative · Future home networks · Indoor · Millimeter-wave · Multiple relay · Relay · Single relay

Z. Genç (✉) · U. H. Rizvi · E. Onur · I. Niemegeers
Wireless and Mobile Communications Group, Delft University of Technology,
2628 CD Delft, The Netherlands
e-mail: z.genc@tudelft.nl

U. H. Rizvi
e-mail: s.u.h.rizvi@tudelft.nl

E. Onur
e-mail: e.onur@tudelft.nl

I. Niemegeers
e-mail: i.niemegeers@tudelft.nl

1 Introduction

The problem of spectrum scarcity has led researchers to explore alternative frequency bands. The 60 GHz band with an unlicensed bandwidth of 5 GHz is an attractive prospective to develop future home networks with multi-gigabit wireless data rates. There are however certain issues with the 60 GHz band that need to be overcome in order to develop wireless communication system in this band. One of the major drawbacks is the high path loss associated with the 60 GHz band. In a typical indoor setting, the line-of-sight (LOS) propagation path between two devices operating at 60 GHz may completely be hindered by surrounding objects and human bodies [1,2]. When a 60 GHz link is blocked, reflections from the surfaces can be exploited to sustain the link connectivity between the devices [3]. The use of the reflected rays burdens additional reflection losses on already very tight link budget and brings complexity to the system. This complexity can not be handled by simple 60 GHz devices, as defined in the ECMA specifications [4], which do not have advanced antenna systems to automatically set up the broken links via reflections.

Another solution to preserve 60 GHz connectivity in case of obstructions is to cooperatively relay the signals via other devices to the destination. Cooperative communications has been recently proposed as a prominent alternative to improve end-to-end performance in wireless cellular and ad hoc networks [5–8]. As its name suggests, the basic idea behind cooperative communications is that mobile terminals can help each other send data from the source to the destination. Therefore, each user's information is retransmitted or relayed by other cooperating terminals. This effectively adds diversity in the system and improves the overall performance. The deleterious impact of channel fading on wireless communications can be mitigated by employing this technique. Signal diversity can be realized in time, frequency or space which facilitates a new form of diversity referred to as cooperative diversity [9]. Decode and forward (DF) and amplify and forward (AF) are two most commonly used and investigated cooperative relaying schemes [9]. In AF, the relay amplifies the received signal and then forwards it to the destination; whereas in DF, the relay decodes the received signal and retransmits the amplified version signal only if no decoding errors occur at the relay. For that reason, DF systems do not amplify the noise and generally have better performance compared to AF.

The performance of wireless cooperative networks employing DF relaying has been extensively reported in the literature [5–9]. The idea of user cooperation diversity with DF and AF protocols was first introduced in [5–8]. The performance of a single relay cooperative network employing both AF and DF protocols in terms of symbol error rate (SER) over Rayleigh fading channels was derived in Su et al. [9]. In this paper, we derive analytical expressions for the error probability of binary phase shift keying (BPSK) signals over Nakagami-m fading channels for an multi relay (N_R) communication network. This is therefore, an extension of Su et al. [9] in two aspects. Firstly, more general fading conditions are considered, i.e., Nakagami-m which in contrast to Rayleigh fading represents LOS as well as non-line-of-sight (NLOS) wireless communication links. Secondly, our expression holds for arbitrary number of relays as opposed to the single relay case considered in Su et al. [9]. Using the analytical expressions for the error probability, we investigate the impact of N_R and the optimal power allocation.

From the 60 GHz facet, a few works explore the opportunities of relaying for the millimeter-wave networks. The effects of using a relay node in multihop fashion are investigated in Genc et al. [10]. Leong et al. propose a pyramid relay system with a single access point at the top of the pyramid and four repeaters at the corners of the base to increase the communication coverage [11]. Singh et al. propose a multihop MAC architecture for 60 GHz wireless personal area networks (WPAN) using relaying to cope with obstructions of LOS links [12].

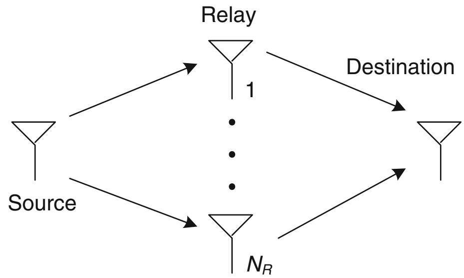


Fig. 1 Simplified system model of an N_R relay cooperative communication network

The problem of 60 GHz link obstruction is also tackled in the Ecma-387 standards, which have been developed for 60 GHz WPANs, by a relay node defined as an advanced "Type A" device with AF capability [4]. None of the above works considers the cooperative relaying for 60 GHz networks.

The remainder of this paper is organized as follows. The impact of the number of relays on the bit error rate (BER) is analyzed in Sect. 2. The system model for cooperative system employing DF relaying is presented, analytical expressions for the error probability are evaluated. The utility of these expressions to find the optimum power allocation and to investigate the impact of N_R on the system performance is presented in Sect. 2.2. The impact of cooperative relaying on the 60 GHz network connectivity is analyzed through simulations in Sect. 3 where the issues of future home networks are taken into consideration. We finalize the paper by summarizing the conclusions in Sect. 4.

2 Multiple Relays in Cooperative Communications

A decode and forward (DF) cooperation protocol employing N_R relays is considered. The simplified cooperation model is depicted in Fig. 1. In this scheme, the source transmits the information symbol with power $P_t^S = P_1$. This information symbol after passing through the fading channel is received by all the relays and the destination. In the second phase, $i-$th relay tries to decode the information symbol and if the decoding is successful it retransmits the same symbol with power $P_t^{R_i} = P_2$. When the symbol detection at the relay is unsuccessful, the relay does not retransmit, in which case $P_t^{R_i} = 0$. After completion of both phases the symbol detection is performed at the destination. In this paper, maximum ratio combining (MRC) is employed at the destination. Furthermore, it is assumed that both the relay and the destination have access to perfect channel state information (CSI). It is also assumed that the wireless devices are in close vicinity, therefore, the path loss is not taken into account. The baseband equivalent received signals at the $i-$th relay and the destination during the first phase are given as

$$y_{sr_i} = h_{sr_i}\sqrt{P_t^S}s + z_{sr_i}, \tag{1}$$

and

$$y_{sd} = h_{sd}\sqrt{P_t^S}s + z_{sd}, \tag{2}$$

respectively, where the fading amplitudes h_{sr_i} and h_{sd} are assumed to independent and identically distributed (i.i.d.) with Nakagami-m distribution. The symbol s denotes the BPSK modulated signal and is chosen from the set $\mathcal{S} \in \{-1, +1\}$. The complex additive white

Gaussian noise (AWGN) z_{sr_i} and z_{sd} has variance $N_0/2$ per dimension. The received signal at the destination from the $i-$th relay is given as

$$y_{r_i d} = h_{r_i d}\sqrt{P_t^{R_i}}\, s + z_{r_i d}. \tag{3}$$

Here again $h_{r_i d}$ denote i.i.d. Nakagami-m fading amplitudes and $z_{r_i d}$ is complex AWGN with variance $N_0/2$ per dimension. The combined relay and source transmit power is kept constant at P, which implies that $P = P_1 + N_R P_2$. Since the total power P is distributed between the relay and the source we can write

$$P_1 = \delta P \ \text{ and } \ P_2 = (1-\delta)\, P/N_R \ \text{ for } \ 0 \le \delta \le 1, \tag{4}$$

where δ denotes the power allocation factor. The total average signal to noise ratio (SNR) at the destination for MRC is given as

$$\gamma_T = P_t^S \frac{E\left[h_{sd}^2\right]}{N_0} + \sum_{i=1}^{N_R} P_t^{R_i} \frac{E\left[h_{r_i d}^2\right]}{N_0} = P_t^S \overline{\gamma} + \sum_{i=1}^{N_R} P_t^{R_i} \overline{\gamma}, \tag{5}$$

where $E[.]$ denotes the expectation operation and the last equality follows from the fact that each channel is assumed to be i.i.d. which implies that $\overline{\gamma} = E\left[h_{sd}^2\right]/N_0 = E\left[h_{r_i d}^2\right]/N_0$. This can be rewritten as

$$\gamma_T = \delta P \overline{\gamma} + \sum_{i=1}^{N_R} \frac{(1-\delta)\, P}{N_R} \overline{\gamma} = P\overline{\gamma}. \tag{6}$$

2.1 Performance Analysis

The error probability of N_R rely cooperative communication network depicted in Fig. 1 can be given as

$$\begin{aligned} P^{\mathcal{D}} = \sum_{\mathcal{B}} P^{\mathcal{D}}\left(\epsilon \,\middle|\, P_t^S = P_1, P_t^{R_1} = b_1 P_2, \ldots, P_t^{R_{N_R}} = b_{N_R} P_2\right) \prod_{i=1}^{N_R} b_i - (-1)^{1-b_i} \\ \times P^{R_i}\left(\epsilon \,\middle|\, P_t^S = P_1\right), \end{aligned} \tag{7}$$

where $P^{\mathcal{D}}\left(\epsilon \,\middle|\, P_t^S, P_t^{R_1}, \ldots, P_t^{R_{N_R}}\right)$ and $P^{R_i}\left(\epsilon \,\middle|\, P_t^S\right)$ denote the power constrained error probability at the destination and the relay, respectively, and the set $\mathcal{B}$ is chosen from the elements $\mathcal{B} \in \left\{b_1, \ldots, b_{N_R}\right\},\ b_i \in \{1, 0\}$. The power constrained error probabilities at the destination and the relay using the moment generating function (MGF) based approach [13] are given as

$$P^{\mathcal{D}}\left(\epsilon \,\middle|\, P_t^S, P_t^{R_1}, \ldots, P_t^{R_{N_R}}\right) = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \mathcal{M}\left(-\frac{P_t^S}{\sin^2(\psi)}\right) \prod_{k=1}^{N_R} \mathcal{M}\left(-\frac{P_t^{R_i}}{\sin^2(\psi)}\right) d\psi \tag{8}$$

and

$$P^{R_i}\left(\epsilon \,\middle|\, P_t^S\right) = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \mathcal{M}\left(-\frac{P_t^S}{\sin^2(\psi)}\right) d\psi \tag{9}$$

respectively, where $\mathcal{M}(\omega)$ denotes the MGF of Nakagami-m PDF and is given as

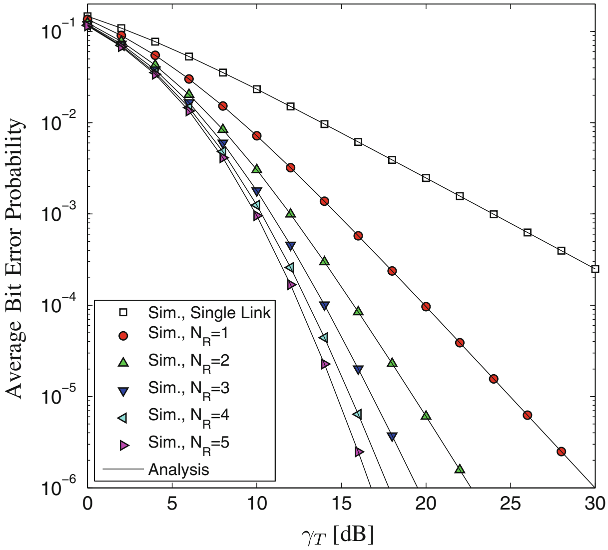


Fig. 2 A comparison of simulation and analysis for DF over Rayleigh ($m = 1$) fading for various values of N_R with $P = 1$, $\delta = 1/2$

$$\mathcal{M}(\omega) = \left(1 - \frac{\omega\overline{\gamma}}{m}\right)^{-m}. \tag{10}$$

Notice that (7) is a generalization of Su et al. [9], in which case only a single relay network with Rayleigh fading was considered. Substituting $N_R = 1$ in (7) and simplifying yields

$$P^{\mathcal{D}} = P^{\mathcal{D}}\left(\epsilon \left| P_t^S = P_1, P_t^{R_1} = 0\right.\right) P^{R_i}\left(\epsilon \left| P_t^S = P_1\right.\right) + \left(1 - P^{R_i}\left(\epsilon \left| P_t^S = P_1\right.\right)\right) \times P^{\mathcal{D}}\left(\epsilon \left| P_t^S = P_1, P_t^{R_1} = P_2\right.\right) \tag{11}$$

which is the same as obtained by Su et al. [9] for BPSK signalling.

2.2 Numerical Results and Discussions

In this section, the analysis is validated with Monte Carlo simulations. The advantages of using relaying in LOS/NLOS scenarios are outlined. Optimized power allocations as functions of the number of relays and the channel fading parameter m are investigated. The results will be presented in terms of BER using (7).

Figures 2 and 3 provide a comparison of the analysis and simulations. The analysis and simulation results are seen to be in good agreement. Therefore, we can use the analysis to accurately evaluate the BER. Furthermore the impressive gains of cooperative communication as compared to the conventional case are also evident from Fig. 2. For example, the DF protocol yields an improvement of about 8 dB at a BER of 10^{-3}, when compared with the conventional case which is a system that does not make use of cooperation.

The second factor that can be used to adjust the system performance is the power allocation δ. Equal power allocation between the source and the relay, i.e., choosing $\delta = 0.5$ may not be the optimal solution. The impact of δ on the BER for a different values of N_R is shown in

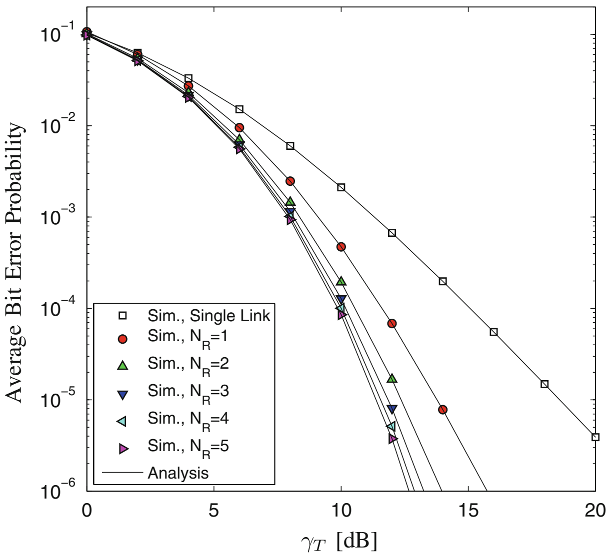


Fig. 3 A comparison of simulation and analysis for DF over Nakagami-m ($m = 3$) fading for various values of N_R with $P = 1$, $\delta = 1/2$

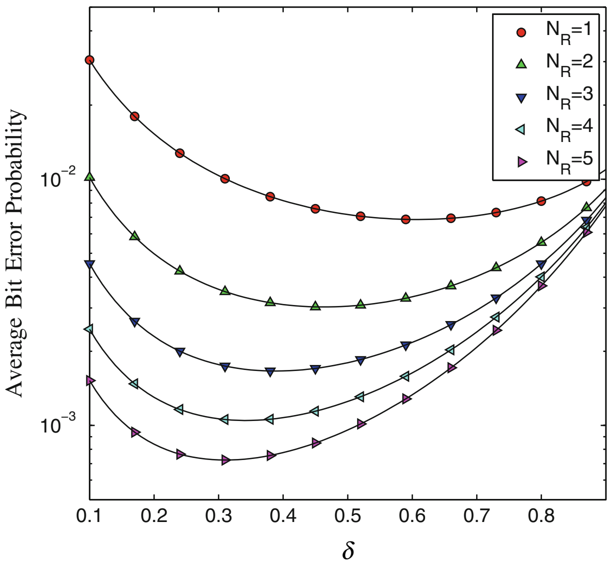


Fig. 4 Performance of DF over Rayleigh ($m = 1$) fading for various values of N_R and δ with $P = 1$, $\gamma_T = 12\,$dB

Figs. 4 and 5. It can be seen that equal power allocation is not the best possible scenario and significant performance gains can be achieved by suitable power allocation.

The number of relays is another valuable resource which should be carefully utilized as more relays require more bandwidth and add to the overall system complexity. Here, we investigate the impact of number of relays on the overall performance. Figure 6 shows the average BER versus the number of relays N_R for various δ values over Rayleigh fading

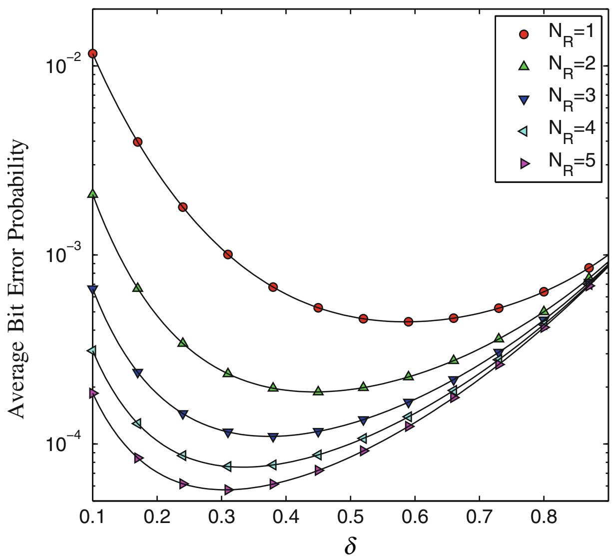


Fig. 5 Performance of DF over Nakagami-m ($m = 3$) fading for various values of N_R and $\delta = 1/2$ with $P = 1$, $\gamma_T = 10\,\text{dB}$

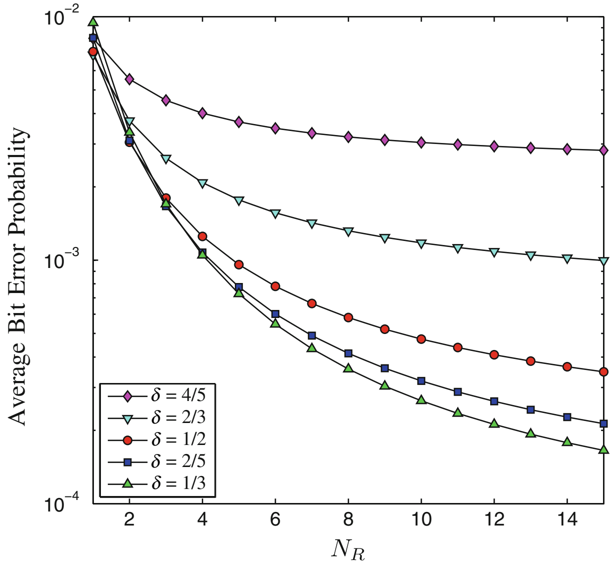


Fig. 6 Performance of DF over Nakagami-m ($m = 3$) fading for various values of N_R and δ with $P = 1$, $\gamma_T = 8\,\text{dB}$

channels. It can be seen after a certain number of relays the improvement in the system performance is negligible. For example, the BER decreases from 10^{-2} to 2×10^{-3} when the N_R is increased from 1 to 5 for $\delta = 2/3$. On the other hand, this improvement becomes negligible for $N_R > 5$.

In this section, we presented the analysis of the impact of relay count on the bit error performance of the system. The presented model can be employed in two-dimensional scenarios where low-rate communication is probable. The obstructions are also generalized in this model; whereas, in future home networks, the obstructions of the communication links in future home networks are mostly due to the humans. In additions, the home networks should be modeled as three dimensional spaces to consider the impact of the floors and ceilings and the reflections thereof. Also, depending on the scenario, the distance to the possible relays are not the same. To take all these considerations into account, we present more generalized cases for the future home networks employing 60 GHz communication technology in the next section. In the next section, instead of BER, we use the outage probability as the performance measure since it gives a better indication about the stability of the 60 GHz links.

3 Cooperative Communications in Future Home Networks

The signal reception in 60 GHz networks is very prone to propagation and penetration losses. Therefore, an investigation of successful signal reception is of paramount importance. One way of analyzing successful signal reception is by computing the outage probability denoted by P_{out}. P_{out} is defined as the probability that the received SNR γ is below a certain specified threshold γ_{Th}. This can be computed via Monte Carlo simulations as

$$P_{\text{out}} = \frac{1}{N_t} \sum_{i=0}^{N_t - 1} \mathcal{L}_i, \tag{12}$$

where N_t denotes the number of trials or simulation runs and the event $\mathcal{L}_i$ is computed as

$$\mathcal{L}_i = \begin{cases} 1, & \text{if } \gamma \leq \gamma_{Th} \\ 0, & \text{if } \gamma > \gamma_{Th} \end{cases}. \tag{13}$$

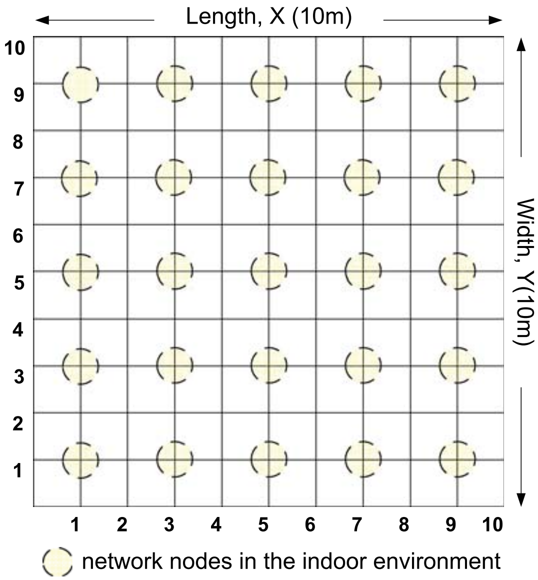
The SNR threshold γ_{Th} is usually chosen to meet some predefined criteria such as the BER. This requires that the SNR corresponding to a certain BER should be chosen. For example, if the system is required to operate at a BER of 10^{-4} then we must choose γ_{Th} as the SNR corresponding to 10^{-4}. A BER of 10^{-4} can be achieved for 60 GHz transmission scenarios with BPSK signalling around 10 dB, which makes us consider $\gamma_{Th} = 10$ dB in the rest of the paper.

We performed the simulations by using the Radiowave Propagation Simulator (RPS) [14]. It is a 3D ray-tracer with a verified accuracy [15]. The 3D ray tracing allows the deterministic prediction of signal levels at intended locations in a more accurate and reliable way compared to empirical radio wave propagation models. Therefore, it can be used to model the channels.

We designed a model indoor environment for the RPS simulations in the size of, 10 m (length) × 10 m (width) × 4 m (height). We defined the dimensions slightly large for a typical living room scenario to better analyze the impacts of relaying. The communication nodes in this environment are modeled as pairs of a transmitter and a receiver with 10 dB antenna gain and 10 dBm transmit power. The bandwidth of the radio channel is set to 2 GHz. We allocated the total transmit power equally between the source and the relay by choosing $\delta = 0.5$. In each scenario, the nodes are placed in a grid-like fashion at the height of one meter as seen in Fig. 7.

In the ray tracing, we only consider the most dominant path, which is the direct path in the LOS case and the strongest reflection path in the NLOS case, between receiver and transmitter by ignoring the multipath components, which are already not very important at 60 GHz [16–18].

Fig. 7 The placement of the network nodes in the simulated indoor environment. Every square unit represents the area of 1m^2



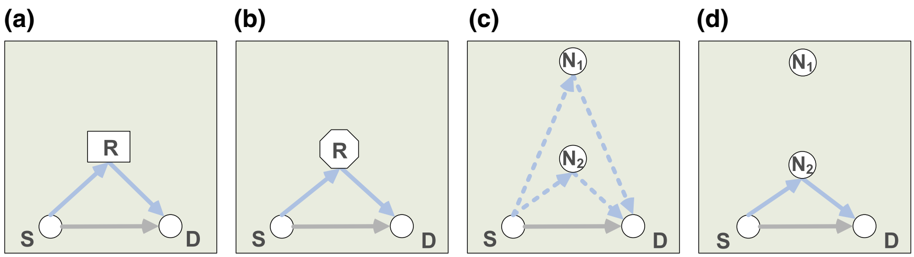


Fig. 8 The demonstration of the single-relay schemes. **a** Relay middle. **b** Relay ceiling. **c** Random node relay. **d** Best node relay

The obstruction was obtained by the human models designed in the shape of rectangular prism with randomly chosen heights (1.60–1.90 m) and widths (40–60 cm). The interior structures of the model rooms are assumed being made of common building materials: concrete for two side walls and the ceiling, plasterboard for two inner side walls, soda-borosilicate for the glass window, wood for the floor and the door. To emulate the propagation behavior of the indoor surfaces, we specify the dielectric parameters of the materials based on the literature [14, 19].

We repeated every simulation 50 times with randomly positioned humans in each run and we calculated the outage probabilities of the nodes based on the measured SNR values.

3.1 Cooperation with a Single Relay

In the first set of simulations, we investigated the impact of the obstacle density on the outage probability of a single relay system for indoor scenarios. We defined the following four relaying schemes where only a single relay is employed as shown in Fig. 8.

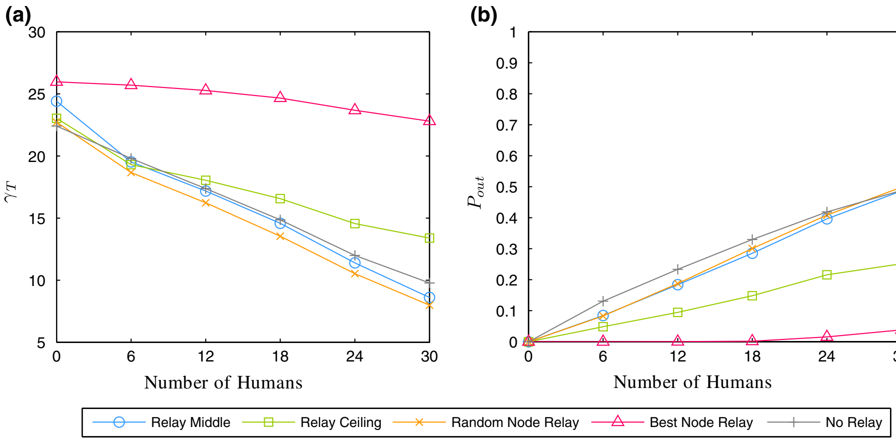


Fig. 9 The SNR and outage achievements of the single relay systems versus obstacle density

- *Relay Middle*: The node in the middle of the network (x:5, y:5, z:1) functions as a dedicated relay device.
- *Relay Ceiling*: A separate relay device is placed in the middle of the ceiling (x:5, y:5, z:4).
- *Random Node Relay*: A random node among the other nodes is chosen as the relay for each link between any two nodes in the network.
- *Best Node Relay*: The node which can provide the best SNR performance as a relay for a particular link is chosen as the relay.

As can be seen in Fig. 9, an outage probability lower than 0.1 in a 60 GHz network may not be achieved even in moderately populated environments without relaying. The deployment of a single relay device in the network improved the outage performance even in random relay selection model which depicts the worst case scenario. In the best case, the *Best Node Relay* scheme achieved the lowest outage rates among all the schemes. The reason behind this superior performance is the fact that there is usually an available node in a 25-node network having clear LOS paths to both ends even in highly populated scenarios. In the comparison of outage performance of the dedicated single relay deployments, the *Relay Ceiling* outperforms the *Relay Middle* scheme by using the advantage of its position which provides it more robust LOS paths with the end nodes. The vicinity of the relay device to the network nodes in the *Relay Middle* scheme enables it to experience lower path loss and hence greater SNR reception in the LOS availability as shown by the average SNR level for less than 6 humans in Fig. 9. However, increasing obstacle density decreases the SNR performance of the *Relay Middle* scheme by blocking the LOS paths and limiting the relay device to the reflections. In the simulations, we observed that the even in case of 1-order reflection, the average reflection loss is around 15 dB for the *Relay Middle* and 20 dB for the *Relay Ceiling* because of the extended transmission path in reflection and the surface losses on the reflective materials. The tight link budgets of the 60 GHz systems can hardly tolerate these high reflection losses.

3.2 Employing Multiple Cooperative Relays

In this set of simulations, we investigated the outage performance of the multiple relay systems in the same settings. We defined five relay schemes containing from two up to ten dedicated relay devices as shown in Fig. 10. These relay schemes are as follows.

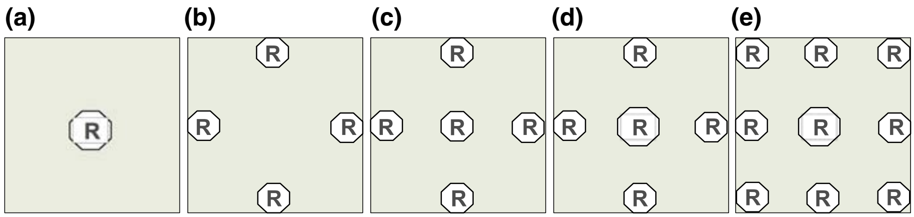


Fig. 10 The demonstration of the multiple relay schemes. **a** Two relays, one in the middle of the area at the height of other nodes and another one in the middle of the ceiling **b** Four relays, four relay devices on the ceiling **c** Five relays, five relay devices on the ceiling **d** Six relays, five relay devices on the ceiling and one relay in the middle of the area at the height of other nodes **e** Ten relays, nine relays on the ceiling and one relay in the middle of the area at the height of other nodes

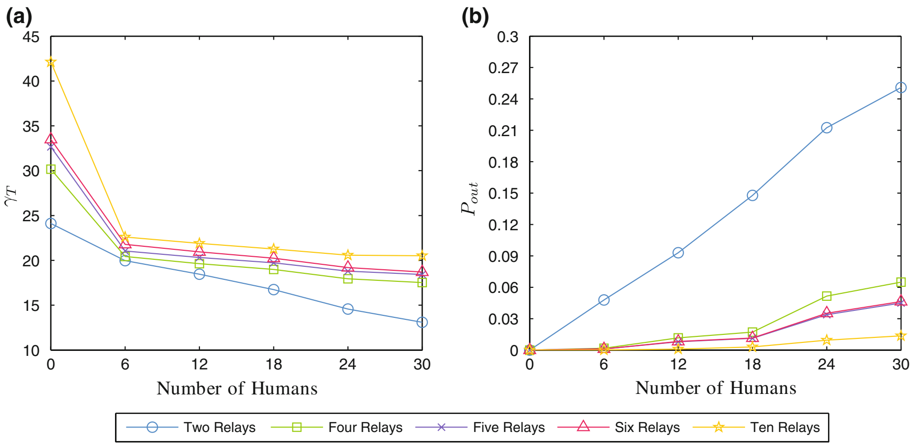


Fig. 11 The SNR and outage probabilities of the multiple-relay systems versus obstacle density

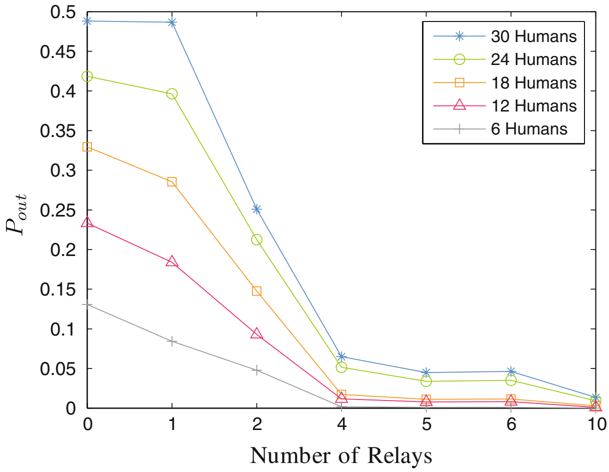
- *Two Relays*: There are two dedicated relay devices, one in the middle of the network (5,5,1) and the other one in the middle of the ceiling (5,5,4).
- *Four Relays*: There are four dedicated relay devices placed in the middle of the ceiling edges, (1,5,4), (9,5,4), (5,1,4) and (5,9,4).
- *Five Relays*: There is one extra dedicated relay devices placed in the middle of the ceiling, (5,5,4), additional to the previous *Four Relays* scheme.
- *Six Relays*: There is one extra dedicated relay devices placed in the middle of the network, (5,5,1), additional to the previous *Five Relays* scheme.
- *Ten Relays*: There are four extra dedicated relay devices placed in the corners of the ceiling, (1,1,4), (1,9,4), (9,1,4) and (9,9,4), additional to the previous *Six Relays* scheme.

As can be seen in Fig. 11, the multiple relay schemes reached to much higher reliability in average compared to the single relay schemes. With the increasing number of humans in the environment, the *Two Relays* scheme suffers more severely from the LOS obstruction and performed higher outage rate than the other schemes especially in the 24 and 30 humans scenarios. The obstacle density in these scenarios also causes a slight difference between the outage performance of other four relay schemes. The difference in the outage probabilities of the *Four Relays* and *Five Relays* schemes shows the contribution of an additional relay device placed in the middle of the ceiling. However, as the performance of *Six Relays* scheme

Table 1 The SNR and outage probability comparison of leading single and multiple relay systems

#Humans	Average SNR [dB]			P_{Outage}		
	No relay	Best node relay	Ten relays	No relay	Best node relay	Ten relays
0	22.41	25.96	42.11	0	0	0
6	19.80	25.69	22.60	0.13	0	0
12	17.37	25.28	21.89	0.23	0.0001	0.0009
18	14.85	24.66	21.28	0.33	0.0018	0.0029
24	11.99	23.67	20.58	0.42	0.0156	0.0094
30	9.78	22.80	20.52	0.49	0.0379	0.0135

Fig. 12 The outage probability for various numbers of relays



shows, adding another relay device at lower height to the *Five Relays* scheme creates a minor impact on the SNR and outage performance. In the last experiment, we studied the performance of *Ten Relays* scheme to observe the impact of placing more relays in the network which has already achieved a very low outage rate. These four relays added to the *Six Relays* scheme increased the SNR and outage performance about 2 dB and 0.03, respectively for the 30-human scenario. When comparing this result with the 5.5 dB SNR and 0.20 outage performance increase obtained by additional four nodes between the *Six Relays* and *Two Relays* schemes, it is seen that adding more relay nodes does not significantly improve the performance of a 60 GHz network if it can already overcome the LOS obstructions. This result is also supported by the performance comparison between the *Ten Relays* scheme and the *Best Node Relay* scheme in Table 1.

When the number of utilized relays increases, the outage probability decreases. Introducing additional relays has a large impact initially. However, as can be seen in Fig. 12, after four relays the outage probability does not change significantly. The effective number of relays is a design parameter which is also dependant on the topology for ad hoc networks. A rigorous analysis is required to determine the effective number of relays since utilization of additional relays increases the performance but also increases the cost and complexity. Additionally, how BER changes when additional relays are utilized is shown in Fig. 6 for various δ values over Rayleigh fading channels. It can be seen after a certain number of relays the improvement in the system performance is negligible which verifies the outage probability analysis.

4 Conclusions

Cooperative communications is a prominent alternative to improve end-to-end performance in future home networks. The basic idea behind cooperative communications is that mobile terminals collaborate to send data of each other. This effectively adds diversity in the system and improves the overall performance. In this paper, we investigate the potential gains of cooperative communication in future home networks. We derive analytical expressions for the error probability of BPSK signals over Nakagami-m fading channels for an N_R relay communication network. Additional to the analytical study, we analyze the contribution of cooperative relaying to the 60 GHz network connectivity through extensive simulations with various relay configurations and obstacle densities.

Impressive gains can be obtained with cooperative communication as compared to the conventional case. For example, the DF protocol yields an improvement of about 8 dB at a BER of 10^{-3}, when compared with the conventional case which is a system that does not make use of cooperation. Equal power allocation is not the best possible scenario and significant performance gains can be achieved by smart power allocation schemes which is left as a future work. After a certain threshold, the additional relays do not contribute to the improvement in the system performance. For example, the BER decreases from 10^{-2} to 2×10^{-3} when the N_R is increased from 1 to 5 for $\delta = 2/3$. On the other hand, this improvement becomes negligible for $N_R > 5$.

An outage probability lower than 0.1 in a 60 GHz network may not be achieved in moderately populated home environments without relaying. For densely populated environments, even a single relay may not provide acceptable outage rates because the LOS paths are obstructed and the relay device is limited with only the reflections. The tight link budgets of the 60 GHz systems can hardly tolerate the large reflection losses.

One solution to achieve outage rates lower than 0.1% in densely populated environments for the 60 GHz networks is deploying relay configurations containing multiple relay nodes. Another solution would be employing a relay selection mechanism which can select the best performing relay node among the network nodes for each 60 GHz link. To successfully maintain such a mechanism, there should be enough number of devices in the network which are capable and willing to cooperate. Considering the vision of Wireless World Research Forum (WWRF) that every person will have a thousand devices by 2017 and most of them will be for short-range communications, it could be reasonable to expect having enough number of devices in the network for cooperation in future home networks. Furthermore, the willingness of the devices for cooperation would not be problem in private home networks.

There is still need for an extensive analysis to determine the optimal number of relays based on the environmental conditions and the topology of the network. Smart cross-layer algorithms can be developed to optimize the cooperation level.

Acknowledgments This research was carried out in the “Future home network” and SiGi Spot projects in IOP GenCom program funded by the Dutch Ministry of Economic Affairs.

References

1. Akeyama, A. (2004 March). Study on mmwave propagation characteristics to realize wpans *IEEE Standardization Document IEEE802.15-04/0094r0*.
2. Collonge, S., Zaharia, G., & Zein, G. E. (2004). Influence of the human activity on wide-band characteristics of the 60 GHz indoor radio channel. *IEEE Transactions on Wireless Communications, 3*(6), 2396–2406.
3. WirelessHD specification version 1.0a, August 2009.
4. ECMA-387 (2008 December). High rate 60 GHz PHY, MAC and HDMI PAL Standard. *ECMA International*.
5. Laneman, J. N., & Wornell, G. W. (2003). Distributed space-time coded protocols for exploiting cooperative diversity in wireless networks. *IEEE Transactions on Information Theory, 49*(10), 2415–2525.
6. Laneman, J. N., & Wornell, G. W. (2004). Cooperative diversity in wireless networks: Efficient protocols and outage behavior. *IEEE Transactions on Information Theory, 50*(12), 3062–3080.
7. Sendonaris, A., Erkip, E., & Aazhang, B. (2003). User cooperation diversity part I. System description. *IEEE Transactions on Communications, 51*(11), 1927–1938.
8. Sendonaris, A., Erkip, E., & Aazhang, B. (2003). User cooperation diversity part II. Implementation aspects and performance analysis. *IEEE Transactions on Communications, 51*(11), 1939–1948.
9. Su, W., Sadek, A. K., & Liu, K. J. R. (2007). Cooperative communication protocols in wireless networks: Performance analysis and optimum power allocation. *Wireless Personal Communications, 44*, 181–217.
10. Genc, Z., Olcer, M.G., Onur, E., & Niemegeers, I. (2010). Improving 60 GHz indoor connectivity with relaying. In *Proceedings of ICC*. May, 23–27.
11. Leong, C. S. C., Lee, B. S., Nix, A. R., & Strauch, P. (2004) A robust 60 GHz wireless network with parallel relaying. In *Proceedings of ICC* (vol. 6, pp. 3528–3532). June, 20–24.
12. Singh, S., Ziliotto, F., Madhow, U., Belding, E. M., & Rodwell, M. J. W. (2007). Millimeter wave WPAN: Cross-layer modeling and multi-hop architecture. In *Proceedings of INFOCOM* (pp. 2336–2340). May, 6–12.
13. Simon, M. K., & Alouini, M.-S. (2004). *Digital communication over Fading Channels*. NY: Wiley.
14. Deissner, J., Hubner, J., Hunold, D., & Voigt, J. (2008) RPS Radiowave Propagation Simulator user manual version 5.4. *Actix GmbH*.
15. Smulders, P., Li, C., Yang, H., Martijn, E., & Herben, M. (2004). 60 GHz indoor radio propagation comparison of simulation and measurement results. In *Proceedings of the 11th IEEE Symposium on Communications and Vehicular Technology*.
16. Xu, H., Kukshya, V., & Rappaport, T. S. (2002). Spatial and temporal characteristics of 60-GHz indoor channels. *IEEE Journal on Selected Areas in Communications, 20*(3), 620–630.
17. Williamson, M. R., Athanasiadou, G. E., & Nix, A. R. (1997). Investigating the effects of antenna directivity on wireless indoor communication at 60 GHz. In *Proceedings of PIMRC* (vol. 2, pp. 635–639). September, 1–4.
18. Manabe, T., Miura, Y., & Ihara, T. (1996). Effects of antenna directivity and polarization on indoor multipath propagation characteristics at 60 GHz. *IEEE Journal on Selected Areas in Communications, 14*(3), 441–448.
19. Langen, B., Lober, G., & Herzig, W. (1994). Reflection and transmission behaviour of building materials at 60 GHz. In *Proceedings of PIMRC* (pp. 505–509). September, 18–23.

Author Biographies

Zülküf Genç received a B.S. degree in Computer Engineering from Istanbul Technical University, Istanbul, Turkey, in 2003 and an M.S. degree in Electrical and Computer Engineering from Koc University, Istanbul, Turkey, in 2006. He is now working towards a Ph.D. in Wireless and Mobile Communications (WMC) Group at the Faculty of Electrical Engineering, Mathematics, and Computer Science (EEMCS) of Delft University of Technology, Netherlands. His research interests include home networks, wireless and mobile communications.

Umar H. Rizvi received the B.S. degree in Electrical Engineering from GIK Institute, Swabi, Pakistan and M.S. degree in Electrical Engineering from Royal Institute of Technology, Stockholm, Sweden. Currently he is working towards the Ph.D. degree in Wireless and Mobile Communication Systems group at Delft University of Technology in Netherlands. His research interests include modulation and coding, signal design and performance analysis for wireless communication systems.

Ertan Onur received the B.S. degree in computer engineering from Ege University, Izmir, Turkey in 1997, and the M.S. and Ph.D. degrees in computer engineering from Bogazici University, Istanbul, Turkey in 2001 and 2007, respectively. Dr. Onur is a BAL'93 graduate. After the B.S. degree, he worked for LMS Durability Technologies GmbH, Kaiserslautern, Germany. During the M.Sc. and Ph.D. degree, he worked as a project leader at Global Bilgi, Istanbul and as an R&D project manager at Argela Technologies, Istanbul. Presently, he is an assistant professor at EEMCS, WMC, Delft University of Technology, Netherlands. Dr. Onur's research interests are in the area of computer networks, collaborative networks, and wireless and sensor networks. He is a member of IEEE.

Ignas Niemegeers got a degree in Electrical Engineering from the University of Gent, Belgium, in 1970. In 1972 he received a M.Sc.E. degree in Computer Engineering and in 1978 a Ph.D. degree from Purdue University in West Lafayette, Indiana, USA. From 1978 to 1981 he was a designer of packet switching networks at Bell Telephone Mfg. Cy, Antwerp, Belgium. From 1981 to 2002 he was a professor at the Computer Science and the Electrical Engineering Faculties of the University of Twente, Enschede, The Netherlands. From 1995 to 2001 he was Scientific Director of the Centre for Telematics and Information Technology (CTIT) of the University of Twente, a multi-disciplinary research institute on ICT and applications. Since May 2002 he holds the chair Wireless and Mobile Communications at Delft University of Technology, where he is heading the Centre for Wireless and Personal Communication (CWPC) and the Telecommunications Department. He was involved in many European research projects, e.g., the EU projects MAGNET and MAGNET Beyond on personal networks, EUROPCOM on UWB emergency networks and, eSENSE and CRUISE on sensor networks. He is a member of the Expert group of the European technology platform eMobility and IFIP TC-6 on Networking. His present research interests are 4G wireless infrastructures, future home networks, ad-hoc networks, personal networks, cognitive networks.