WiMAX Network Design for Cost Minimization and Access Data Rate Guarantee Using Multi-hop Relay Stations

Chutima Prommak and Chitapong Wechtaison

Abstract—Network cost and network quality of services are important concerns in the widespread deployment of WiMAX networks. This paper presents a novel network design and optimization model for mobile WiMAX access networks utilizing multi-hop relays. The proposed model aims to determine optimal locations of base stations and relay stations so that the network can guarantee quality of services in term of the access data rate and the service coverage to serve potential user traffic demand in the target service area. Numerical network design results demonstrate that the proposed model can improve the user access data rate up to 60% and enhance the network service coverage up to 12% compared with the other existing models in literature.

Keywords—WiMAX, Access networks, Network optimization, Network design, Wireless Networks.

I. INTRODUCTION

WiMAX (Wireless Interoperability for Microwave Access) network technology has become potential solutions to bring broadband internet access to people in the remote area where a wired network infrastructure cannot reach [1], [2]. With the support of the IEEE 802.16j standard, one can deploy the network topology using multi-hop relay stations (RSs) to enhance services of the base stations. As illustrated in Fig.1, RSs can provide coverage extension to the cell boundary area, the shadowing area and the coverage-hole area [1], [2]. To enable network operators to provide low cost coverage with the quality of services guarantee, there is a need for an efficient network design.

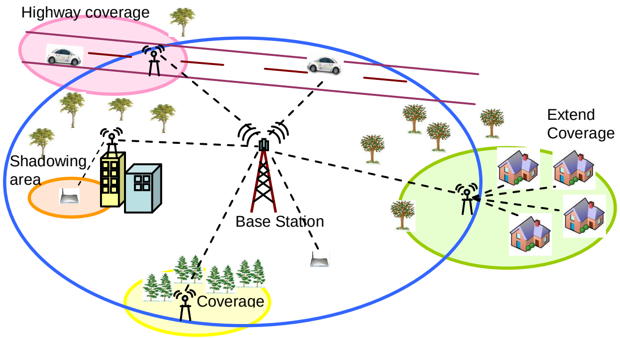

Fig.1 Relay station deployment

Several works have devoted to the studies of the performance improvement of wireless networks and the wireless network design problems. In [3], the authors propose an adaptive cross-layer bandwidth scheduling strategies for the hierarchical cellular networks. [4] presents a study of the baseband transceiver for WIMAX IEEE802.16d. Research works in [5-16] deal with the wireless network design problems. [5-7] present the studies of the radio network planning for cellular networks. In [8-12], the authors consider WiMAX radio network planning and present the practical network deployment with performance analysis and evaluation. Although the results give insight of the real network performance, the mathematical model was not used to optimize the network installation. Later works in [13-15] proposed mathematical models for the base station (BS) placement problems. The objective was to minimize the network cost but the multi-hop relay topology was not considered.

In [16], the authors proposed an Integer Programming formulation dealing with the BS and RS placement problem for the WiMAX multi-hop relay networks. The objective was to determine the locations of BSs and RSs by minimizing the network cost and the normalized path losses between the user demand locations and BS/RS locations. While their contribution is significant, the proposed planning method could not provide quality of services guarantee. For this reason, efficient WiMAX network design techniques are needed.

In our paper we propose a novel WiMAX network design approach, accounting for the quality of services guarantee in the design process. Specifically, we aim to solve the BS and RS placement problem (BRPP) for the WiMAX networks that can guarantee the network service coverage and the physical bit rate to the target users by deploying not only the BSs but also the multiple hop RSs in the WiMAX networks.

The rest of the paper is organized as followed. Section II provides the problem definition and describes the problem formulation. Section III explains the numerical experiments. Section IV presents numerical results and discussion which focus on the performance of the different network planning models. Finally, section V concludes the paper.

II. PROBLEM FORMULATION

The problems of WiMAX network design are defined and mathematically formulated as follows:

A. Problem Definition

In the WiMAX network design, we consider the BS and RS Placement Problem (BRPP) which involve selecting locations to install the BSs and the RSs from candidate sites of BS and RS, respectively.

The multiple-hop network configuration is formed in the way that the users can access the network directly through the BSs or indirectly via the RSs which connect to the BSs. Specifically, the proposed model aims to determine the minimum number of BSs and RSs to be installed in the target service area of the WiMAX networks so that the multi-hop relay network configuration can be formed and the resulting networks can guarantee the quality of services in term of the user access rate and the network service coverage.

In the network design model, we consider that BSs and RSs operate at the same transmitting power (a specified value). We consider that the user demand is modeled by Demand Points (DPs) which represent the geographic distribution of the expected user traffic in the service area and the target service area is represented by a set of discrete grid points called Signal Test Points (STPs) at which the received signal strength is tested. The network quality of services in term of the user access rate and the network service coverage are incorporated in the model via the received sensitivity requirement at DPs and STPs, respectively. Such requirements in turn provide the user access rate guarantee.

B. Problem Formulation

The WiMAX network design problem is formulated as an Integer Linear Programming (ILP) model, denoted as a BRPP model. Table I shows the notation used in the model. The BRPP model aims to minimize the network cost, including the BS and RS installation cost. This can be written as the objective function (1).

$$Minimize \sum_{\forall j \in B} F_j \beta_j + \sum_{\forall i \in R} E_i \gamma_i \qquad (1)$$

We incorporate the network design requirements into the mathematical model through three sets of constraints, denoted *C1*, *C2*, and *C3*. *C1* consists of constraints that ensure the network service coverage. *C2* is a set of constraints that guarantee the user traffic accommodation and the access rate requirements. The last set *C3* consists of constraints that ensure the BS-RS connections.

Table I Notation

Sets:	
B	A set of candidate sites to install base stations (BSs)
R	A set of candidate sites to install relay stations (RSs)
D	A set of demand points (DPs)
T	A set of best signal test points (STPs)
Decision variables:	
β_j	A binary {0, 1} variable that equals 1 if the BS is installed at site j, $j \in B$; 0 otherwise
γ_i	A binary {0, 1} variable that equals 1 if the RS is installed at site I, $i \in R$; 0 otherwise
u_{hj}	A binary {0, 1} variable that equals 1 if the STP h is assigned to BS j, $h \in T$ and $j \in B$; 0 otherwise
v_{hi}	A binary {0, 1} variable that equals 1 if the STP h is assigned to RS I, $h \in T$ and $i \in R$; 0 otherwise
x_{gj}	A binary {0, 1} variable that equals 1 if the DP g is assigned to BS j, $g \in D$ and $j \in B$; 0 otherwise
y_{gi}	A binary {0, 1} variable that equals 1 if the DP g is assigned to RS I, $g \in D$ and $i \in R$; 0 otherwise
w_{ij}	A binary {0, 1} variable that equals 1 if the RS I is assigned to BS j, $i \in R$ and $j \in B$; 0 otherwise
Constant parameters:	
F_j	Cost to install base station j, $j \in B$
E_i	Cost to install relay station i, $i \in R$
P_t	The received signal strength threshold for STPs
P_d	The received signal strength threshold for DPs
P_r	The received signal strength threshold for RSs
P_{hj}	The signal strength that a STP h receives from BS j, $h \in T$ and $j \in B$
P_{hi}	The signal strength that a STP h receives from RS i, $h \in T$ and $i \in R$
P_{gj}	The signal strength that a DP g receives from BS j, $g \in D$ and $j \in B$
P_{gi}	The signal strength that a DP g receives from RS i, $g \in D$ and $i \in R$

C1: Network service coverage

$$\sum_{\forall j \in B} u_{hj} + \sum_{\forall i \in R} v_{hi} \geq 1 \qquad , \forall h \in T \qquad (2)$$

$$u_{hj} \leq \beta_j \qquad , \forall h \in T,\ \forall j \in B \qquad (3)$$

$$v_{hi} \leq \gamma_j \qquad , \forall h \in T,\ \forall i \in R \qquad (4)$$

$$u_{hj}\left(P_{hj} - P_t\right) \geq 0 \qquad , \forall h \in T,\ \forall j \in B \qquad (5)$$

$$v_{hi}\left(P_{hi} - P_t\right) \geq 0 \qquad , \forall h \in T,\ \forall i \in R \qquad (6)$$

Constraints (2) – (6) ensure that the network can provide signal coverage in the target service area by assessing the signal strength at each STP *h* and specifying that the signal strength received at STP *h* from BS *j* or RS *i* must be greater than the threshold P_t.

C2: User traffic accommodation and access rate guarantee

$$\sum_{\forall j \in B} x_{gj} + \sum_{\forall i \in R} y_{gi} \geq 1 \qquad , \forall g \in D \qquad (7)$$

$$x_{gj} \leq \beta_j \qquad , \forall g \in D,\ \forall j \in B \qquad (8)$$

$$y_{gi} \leq \gamma_j \qquad , \forall g \in D,\ \forall i \in R \qquad (9)$$

$$x_{gj}\left(P_{gj} - P_d\right) \geq 0 \qquad , \forall g \in D,\ \forall j \in B \qquad (10)$$

$$y_{gj}\left(P_{gj} - P_d\right) \geq 0 \qquad , \forall g \in D,\ \forall i \in R \qquad (11)$$

Constraints (7) – (11) specify that the network can accommodate all predicted traffic demand and guarantee the user access rate. These constraints ensure that the signal strength that user at DP *g* receives from the BS *j* or the RS *i* is greater than the threshold P_d so that the physical transmission data rate can be achieved.

C3:BS-RS connections

$$\sum_{\forall j \in B} w_{ij} = \gamma_i \qquad , \forall i \in R \qquad (12)$$

$$w_{ij} \leq \beta_j \qquad , \forall i \in R,\ \forall j \in B \qquad (13)$$

$$w_{ij}\left(P_{ij} - P_r\right) \geq 0 \qquad , j \in B,\ \forall i \in R \qquad (14)$$

Constraints (12) – (14) enforce BS-RS connection. Constraint (12) ensures that each RSs can connect to only one BS. Constraint (13) ensures that RSs connect to BSs that are installed. Finally, constraint (14) ensure that the signal strength that between RS *i* and BS *j* is greater than the threshold P_r.

III. NUMERICAL EXPERIMENTS

In this section we present numerical study and analysis demonstrating the WiMAX network design using the proposed BRPP model. We compare our model with those presented in [16] of which the objective function is to minimize the weighted functions of the installation cost and the path loss. We call this a Weighted Objective Function (WOF) approach. Our model, on the other hands, aims to minimize the installation cost but does not minimize path loss. In stead, we incorporate the path loss function in the constraints where we calculate the received signal strength to guarantee the signal strength level that can ensure the minimum user access data rate requirement provided by the resulting WiMAX networks.

A. Description

In numerical experiments, we use the design scenarios of the service area of size 3km×3km as shown in Fig.2. The number of candidate sites to install BSs and RSs are 20 and 60, respectively. There are 200 DPs and 256 STPs (grid size of 200m×200m). We consider the cost of each BS and RS are $120,000 and $40,000 which are an approximate cost from typical suppliers [17]. We consider the WiMAX standards IEEE 802.16. Table II shows the parameters used in the numerical studies (see [17] for more details). Table III presents the minimum received signal strength (in dBm) to be

Table II Parameters Used in Numerical Experiments

Parameters	Value
Height of BSs and RSs	60 m
Height of TPs	2 m
Transmitted Power	35 dBm
Transmitted antenna gain	16 dBi
Received antenna gain	2 dBi
Frequency	2.5 GHz
Terrain type	C
Bandwidth	3.5 MHz
Data rate requirement for DPs	12.71 Mbps
Data rate requirement for STPs	5.64 Mbps
Cost of each base station	120,000 $
Cost of each relay station	40,000 $

Table III Receiver Sensitivity Threshold for Physical Bit Rate Requirement (Alvarion BreezeMAX at 3.5 MHz)

Modulation techniques	Physical bit rate (Mbps)	Receiver sensitivity threshold (dBm)
BPSK 1/2	1.41	-100
BPSK 3/4	2.12	-98
QPSK 1/2	2.82	-97
QPSK 3/4	4.23	-94
QAM 16 1/2	5.64	-91
QAM 16 3/4	8.47	-88
QAM 64 2/3	11.29	-83
QAM 64 3/4	12.71	-82

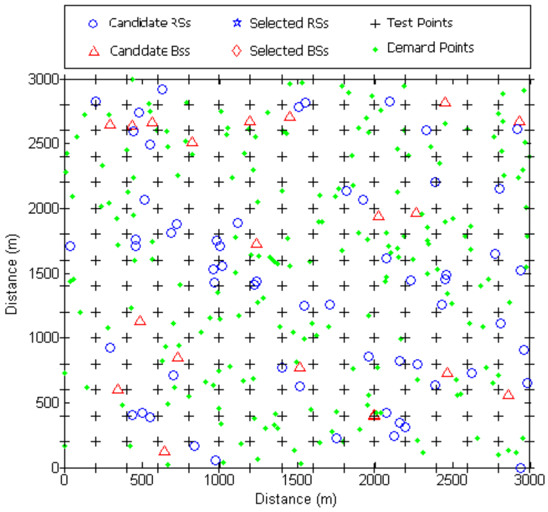

Fig.2 Numerical experiment setup.

able to achieve a certain physical access rate according to the choices of modulation techniques. The transmit power of each BS and RS used for the tests are 35 dBm which are typical values used in the WiMAX networks [10].

B. Propagation Model

It is necessary to compute the received signal strength at DPs and STPs and input the obtained values in the BRPP model to find the optimal locations to install BSs and RSs. This computation can be done by using the propagation model.

In this paper we use the Stanford University Interim (SUI) model which is recommended by the IEEE 802.16 to evaluate the path loss in WiMAX networks [18]. The SUI path loss equation is presented in [18], [19]. The path loss equation is written here in Eq. (15). Table IV describes notation used in the SUI model. It computes the propagation loss as a function of the distance, *d*, between the transmitter and the receiver. It uses correction factors X_f and X_h for the operating frequency and the receiver antenna height. Additionally, the SUI model takes into account the network environment (terrain) via the use of the path loss exponent *n*. The network environment is classified into three types, namely A, B, and C. Type A characterizes the hilly terrain with medium to high tree density. Type B characterizes the flat terrain with medium to high tree density or the hilly terrain with light tree density. Type C characterizes the flat terrain with light tree density. The path loss exponent, *n*, for the specified terrain type is computed by Eq. (17) of which the values of the constant parameter *a*, *b* and *c* are given in Table V.

$$PL = A + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_f + X_h + s \qquad (15)$$

$$A = 20\log_{10}\left(\frac{4\pi d_0}{\lambda}\right) \qquad (16)$$

$$n = a - bh_b + c / h_b \qquad (17)$$

$$X_f = 6.0\log_{10}\left(\frac{f}{2000}\right) \qquad (18)$$

$$X_h = -10.8\log_{10}\left(\frac{h_r}{2}\right) \quad \text{For terrain type A, B} \qquad (19)$$

$$X_h = -20.0\log_{10}\left(\frac{h_r}{2}\right) \quad \text{For terrain type C} \qquad (20)$$

Table IV Notation used in the SUI model

Notation	Definition
A	Path loss at the reference distance d_0
N	Path loss exponent
D	Distance (m.) between the transmitter and the receiver
D_0	Reference distance (100 m.)
X_f	Correction factors for the operating frequency
X_h	Correction factors for the receiver antenna height
s	Shadow fading factor (dB)
h_b	Transmitter antenna height (m.)
h_r	Receiver antenna height (m.)
f	Operating frequency

Table V Parameters used in the SUI model

Parameter	Terrain A	Terrain B	Terrain C
a	4.6	4	3.6
b	0.0075	0.0065	0.0050
c	12.6	17.1	20
s	10.6 dB	9.6 dB	8.2 dB
s_{95}	17.4 dB	15.8 dB	13.5 dB

IV. NUMERICAL RESULTS AND ANALYSIS

We input the set of BS and RS candidate sites and other parameters to the BRPP model. We then solve the WiMAX network design by implementing the BRPP model with the ILOG-OPL development studio and solving with CPLEX 5.2 optimization solver. Computations are performed on an Intel Centrino Core2 Duo Processor 2.0 GHz and 2GB of RAM. The following shows numerical results and analysis.

A. Network Configuration

Fig.3 shows the WiMAX network configuration designed by the BRPP model. It depicts the selected sites to install BSs and RSs. By using four BSs and six RSs in the resulting configuration, we can achieve 100% service coverage through out the required area and guarantee the physical access rate to all DPs in the area. The cost of the resulting network is $768,000. Fig.4 shows the service coverage area of the resulting network. It is represented by the coverage of STPs. Fig.5 shows the DP coverage. It demonstrates the data rate guarantee to users in the coverage area.

B. Network Performance Comparison

Table VI shows numerical results comparing the network design using the BRPP model and that using the WOF model [16]. The performance matrices used for the comparison included the network cost, the number of installed BSs and RSs, and the quality of services in term of the user access rate guarantee and the service coverage guarantee. The results show that although the BRPP model yields the network cost higher than that of the WOF model, the BRPP model yields the network configuration that can guarantee the user access data rate 60% higher than that designed by the WOF model. Furthermore, the network designed by the BRPP model can provide 100% service coverage which is more than 10% higher than that designed by the WOF model.

C. Effects of User Access Rate Requirements

Table VII shows numerical results comparing various cases of the network design imposing different conditions on the data rate requirements. The results show tradeoffs between the network cost and the achievable user data rate. In case that the network operators want to provide the service access rate at 12.71 Mbps throughout the service area (represented by DPs and STPs), the network cost would be about 6% higher than the case that only providing the service rate at 12.71 Mbps to the area with high density of target users (represented by DPs) whereas the other areas (represented by STPs) guarantee the access rate at 5.64 Mbps. Comparing to the case that imposes the data rate guarantee at 5.64 Mbps over the whole service area, the network cost is 62% lower than the case imposing the data rate guarantee at 12.71 Mbps in the service area.

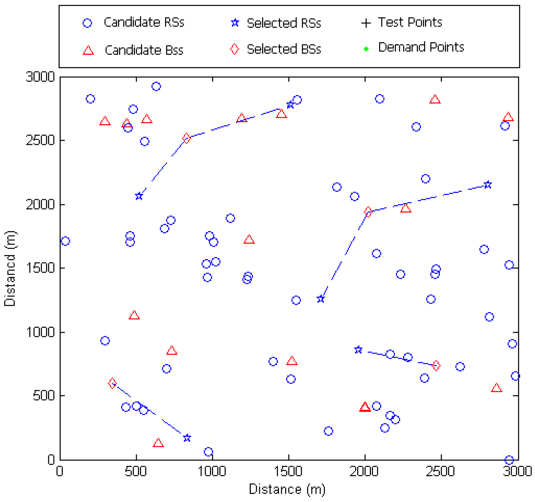

Fig.3 Selected BS and RS sites

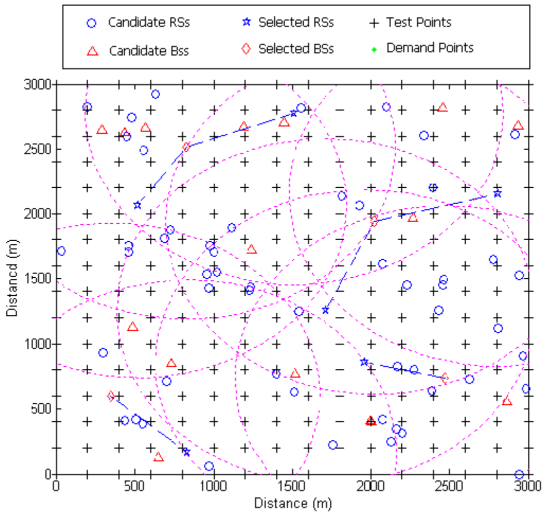

Fig.4 Service area guarantee representing by coverage of STPs

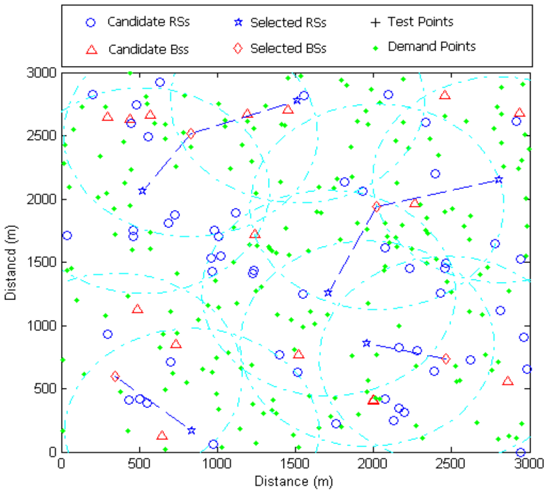

Fig.5 Data rate guarantee representing by coverage of DPs

Table VI Result Comparison

Parameter Name	BRPP model	WOF model
Installation cost	768,000$	264,000$
Number of BSs used	4	1
Number of RSs used	6	3
Number of served DPs	200	80
Number of served STPs	256	226
Guarantee user access data rate	100%	40%
Guarantee service coverage	100%	88.28%

Table VII Vary User Access Rate Requirement

Data Rate Requirement (Mbps)		Network Cost ($\$10^5$)	Number of BSs used	Number of RSs used
at DP	at STP			
2.71	12.71	8.16	4	7
12.71	5.64	7.68	4	6
5.64	5.64	3.12	1	4
2.82	2.82	1.68	1	1

D.Signal Propagation Characteristics

The received signal strength at DPs and STPs were evaluated by using the SUI path loss model [18]. Different network configurations yield different signal propagation characteristics in the service area. Fig.7 shows the probability density function of the received signal strength obtained from the network designed by the BRPP model, compared with that designed by the WOF model. We can see that the network configuration designed by the BRPP model yields better signal quality at DPs and STPs than those of the WOF model.

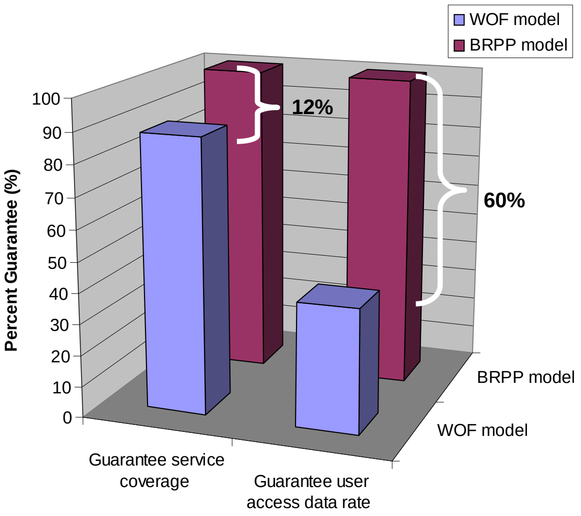

Fig.6 Result comparison

V.CONCLUSION

This paper presents a novel mathematical model for an efficient design of the WiMAX network using multi-hop relay topology. We formulate the problem as an Integer Linear Programming problem. The objective is to minimize the network installation cost and guarantee the quality of services in term of the user access rate and the network service coverage. From numerical results we can conclude that incorporating the network design requirements into the constraints of the mathematical model can greatly improve the quality of services of the resulting networks in term of the user access rate and the network service coverage. However, it would be interesting to investigate other approaches for the WiMAX network design. We currently explore effects of the budget limitation on the network performance optimization.

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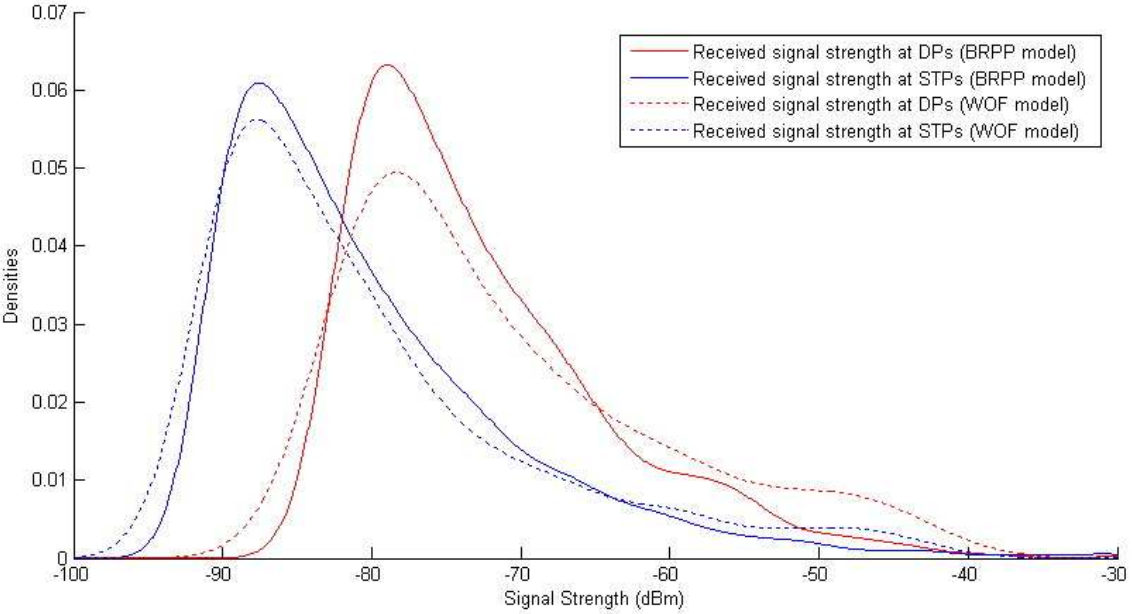

Fig.7 Signal propagation characteristic comparison

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