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Wireless Multi-hop Network Scenario Emulation with MinGenMax Error Based on Interval Equivalent Character of Wireless Communication

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Abstract

This paper proposes a novel approach to emulate an arbitrary wireless multi-hop network scenario in a fixed wireless test-bed, in which every node is equipped with a variable attenuator. We take notice of the interval equivalent character of wireless communication and consider the wireless multi-hop scenario emulation problem as an interval equivalent emulation problem. We define the generalized error, which is an error of a value relative to an interval, formulate the MinGenMax (Minimize Generalized Maximum) error problem and propose an optimum algorithm.

Index Terms: Computer architecture; wireless multi-hop network emulation; minimize generalized maximum error; interval equivalent

1. Introduction

In order to obtain reality, [1][2] provide wireless emulators by using attenuators, but they did not discuss how to configure attenuators to emulate arbitrary wireless multi-hop networks. In [3] [4], we discuss how to emulate an arbitrary wireless multi-hop network scenario by configuring variable attenuators which are equipped on the nodes in a fixed test-bed (see Fig. 1). We consider the emulation as a point-value emulation problem and minimize the maximum error of path loss of wireless links to obtain an effective emulation scenario.

In this paper, we take notice of the interval equivalent character of wireless communication, formulate the problem as an interval equivalent emulation problem, and propose an optimum algorithm.

2. Problem Statement

Equipping fixed nodes with attenuators, we can emulate a desired T-R separation distance by adjusting path loss, which is the difference of transmitter power and receiver power measured in dB [5].

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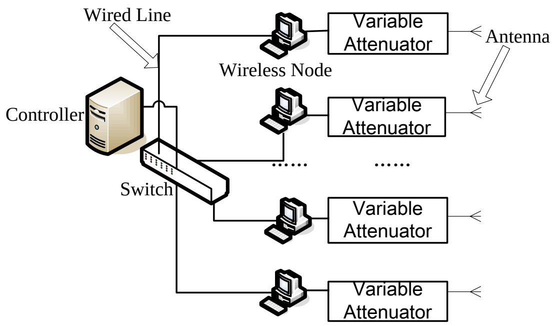

Fig 1. Emulator with variable attenuators.

$$\overline{PL}_{i,j}^{(emu)}[dB] = \overline{PL}_{i,j}^{(fix)}[dB] + x_i + x_j \quad (1)$$

where x_i and x_j are attenuator parameters of node i and node j, $\overline{PL}_{i,j}^{(fix)}$ is the average real path loss of the link between these two nodes, and $\overline{PL}_{i,j}^{(emu)}$ is the average emulating path loss.

In fact, wireless communication has the interval equivalent character. If the pass loss of a user-desired wireless link is $\overline{PL^{(user)}}$, then there exists a minimum value $\overline{PL_{\text{lb}}}$ and a maximum value $\overline{PL_{\text{rb}}}$, the communication performance of any wireless link with pass loss value in $[\overline{PL_{\text{lb}}}, \overline{PL_{\text{rb}}}]$ closed interval is similar to the user-desired link. So it is not necessary to let the path loss of the emulating wireless link $\overline{PL^{(emu)}}$ be equal to $\overline{PL^{(user)}}$, but $\overline{PL^{(emu)}} \in [\overline{PL_{\text{lb}}}, \overline{PL_{\text{rb}}}]$ is enough. We use path loss of links between every two nodes in an n-node wireless multi-hop network $\overline{PL}_{i,j}{}_{\,i,j=1,\ldots,n, i\neq j}$ to represent the network. Then we formulate the wireless multi-hop network scenario emulation problem as the following interval equivalent emulation problem.

M, N are integers and $3 \le M \le N$. Given an $N-\text{node}$ fixed wireless test-bed $\overline{PL}_{i,j}^{(fix)}{}_{\,i,j=1,\ldots,N, i\neq j}$, an $M-\text{node}$ user-defined wireless multi-hop network $\overline{PL}_{i,j}^{(user)}{}_{\,i,j=1,\ldots,M, i\neq j}$, the adjustable scale of attenuators $[x_{\min}, x_{\max}]$, and the interval equivalent functions of average pass loss $f_{lb}(\overline{PL})$, $f_{rb}(\overline{PL})$. Find an M-node subset from N-node, which constitutes the network $\overline{PL}_{i,j}^{(0)}{}_{\,i,j=1,\ldots,M, i\neq j}$, and the M attenuator-parameters $x_1, x_2, \ldots, x_M$, such that the generalized maximum error is a minimum, which can be expressed by the following expression.

$$\min_{[\overline{PL_{i,j}}]^{(0)}_{M*M}}\left(\min_X\left(\max_{i,j=1,\dots,M,i\neq j}\left(\max\left(\begin{array}{l} f_{lb}\left(\overline{PL^{(user)}_{i,j}}\right)-\left(\overline{PL^{(0)}_{i,j}}+x_i+x_j\right), \\ \left(\overline{PL^{(0)}_{i,j}}+x_i+x_j\right)-f_{rb}\left(\overline{PL^{(user)}_{i,j}}\right),0\end{array}\right)\right)\right)\right)$$

It can be seen that, the generalized error is an error of a value relative to an interval.

We call this wireless multi-hop network scenario emulation problem WMNSE-MGME (Wireless Multi-hop Network Scenario Emulation - Minimizing Generalized Maximum Error).

3. Solution Analysis

The solution process can be divided into two steps. In the first step, the optimum attenuator-parameters subject to minimize the generalized maximum error for each permutation of M - node subsets from $N -$ node is computed. In the second step, the optimum permutation whose MinGenMax error is the minimum in all permutations is selected. We call the problem in the first step WMNSE-MGME-CP (WMNSE-MGME Core Problem), and it can be formulated as the following optimization problem.

Denote $X=(x_1,\dots,x_M)\in R^M$.

Minimize

$$f_0(X)=\max_{i,j=1,\dots,M,i\neq j}\left(\max\left(c^{(lb)}_{i,j}-(x_i+x_j),(x_i+x_j)-c^{(rb)}_{i,j},0\right)\right)$$

where,

$$[c_{i,j}]^{(lb)}_{M*M}=[f_{lb}(\overline{PL_{i,j}})]^{(user)}_{M*M}-[\overline{PL_{i,j}}]^{(0)}_{M*M} ,$$

$$[c_{i,j}]^{(rb)}_{M*M}=[f_{rb}(\overline{PL_{i,j}})]^{(user)}_{M*M}-[\overline{PL_{i,j}}]^{(0)}_{M*M}$$

Subject to $x_{\min}\le x_i\le x_{\max}$, $i=1,\dots M$

Obviously, the constraint set is convex [6]. The objective function is convex too, because $\forall\lambda(0<\lambda<1)$

$$
\begin{aligned}
& f_0\left(\lambda X^{(1)} + (1-\lambda)X^{(2)}\right) \\
&= \max_{i,j=1,...,M,i\neq j} \\
&\left(\max\left(\begin{array}{l} c_{i,j}^{(lb)} - \left(\lambda x_i^{(1)} + (1-\lambda)x_i^{(2)} + \lambda x_j^{(1)} + (1-\lambda)x_j^{(2)}\right), \\ \left(\lambda x_i^{(1)} + (1-\lambda)x_i^{(2)} + \lambda x_j^{(1)} + (1-\lambda)x_j^{(2)}\right) - c_{i,j}^{(rb)}, 0 \end{array} \right)\right) \\
&= \max_{i,j=1,...,M,i\neq j} \\
&\left(\max\left(\begin{array}{l} \lambda\left(c_{i,j}^{(lb)} - \left(x_i^{(1)} + x_j^{(1)}\right)\right) + (1-\lambda)\left(c_{i,j}^{(lb)} - \left(x_i^{(2)} + x_j^{(2)}\right)\right), \\ \lambda\left(\left(x_i^{(1)} + x_j^{(1)}\right) - c_{i,j}^{(rb)}\right) + (1-\lambda)\left(\left(x_i^{(2)} + x_j^{(2)}\right) - c_{i,j}^{(rb)}\right), \\ \lambda * 0 + (1-\lambda) * 0 \end{array} \right)\right) \\
&\leq \max_{i,j=1,...,M,i\neq j} \\
&\left(\begin{array}{l} \lambda \max\left(c_{i,j}^{(lb)} - \left(x_i^{(1)} + x_j^{(1)}\right), \left(x_i^{(1)} + x_j^{(1)}\right) - c_{i,j}^{(rb)}, 0\right) + \\ (1-\lambda) \max\left(c_{i,j}^{(lb)} - \left(x_i^{(2)} + x_j^{(2)}\right), \left(x_i^{(2)} + x_j^{(2)}\right) - c_{i,j}^{(rb)}, 0\right) \end{array} \right) \\
&\leq \lambda \max_{i,j=1,...,M,i\neq j} \\
&\left(\max\left(c_{i,j}^{(lb)} - \left(x_i^{(1)} + x_j^{(1)}\right), \left(x_i^{(1)} + x_j^{(1)}\right) - c_{i,j}^{(rb)}, 0\right)\right) + \\
&(1-\lambda) \max_{i,j=1,...,M,i\neq j} \\
&\left(\max\left(c_{i,j}^{(lb)} - \left(x_i^{(2)} + x_j^{(2)}\right), \left(x_i^{(2)} + x_j^{(2)}\right) - c_{i,j}^{(rb)}, 0\right)\right) \\
&= \lambda f_0\left(X^{(1)}\right) + (1-\lambda) f_0\left(X^{(2)}\right)
\end{aligned}
$$

Therefore we can obtain a global optimum solution of WMNSE-MGME-CP by reducing the objective function value iteratively, and get an optimum solution of WMNSE-MGME by comparing the minimized generalized maximum errors of all M - node subset permutations and selecting the minimum.

4. Optimum Algorithm

The *perPermMinGenMaxError* algorithm is an optimum algorithm to address WMNSE-MGME-CP. The key idea of this algorithm is similar to the optimum algorithm in [3], which iteratively reduce the value of the objective function until that value can not be reduced by adjusting any of the variables. The main difference is that, the maximum error in [3] is an error of a value relative to a value, but the generalized maximum error in this paper is an error of a value relative to an interval.

Algorithm *perPermMinGenMaxError*

Input: $\overline{PL}^{(0)}_{i,j}\ _{i,j=1,...,M,i\neq j}$, $\overline{PL}^{(user)}_{i,j}\ _{i,j=1,...,M,i\neq j}$, $x_{\min}$, $x_{\max}$, $f_{lb}\left(\overline{PL}\right)$, $f_{rb}\left(\overline{PL}\right)$ and the computation precision ε

Output: $X=(x_1,x_2,...,x_M)$.

Begin

1. Initial $x_i = min(0,x_{min}), i=1...M$, $[c_{i,j}]^{(lb)}_{M*M} = [f_{lb}(\overline{PL_{i,j}})]^{(user)}_{M*M} - [\overline{PL_{i,j}}]^{(0)}_{M*M}$, $[c_{i,j}]^{(rb)}_{M*M} = [f_{rb}(\overline{PL_{i,j}})]^{(user)}_{M*M} - [\overline{PL_{i,j}}]^{(0)}_{M*M}$

2. $e^{(lb)}_{i,j} = c^{(lb)}_{i,j} - (x_i + x_j)$, $e^{(rb)}_{i,j} = (x_i + x_j) - c^{(rb)}_{i,j}$, $i,j=1...M, i\neq j$

   $AdjR_i = true, Num=0, ToCheck_i = -1,$

   $i=1...M$

3. Seek $\max\limits_{i,j=1,...,M,i\neq j}\left(e^{(lb)}_{i,j}, e^{(rb)}_{i,j}\right)$, record as $e_{line,row}$

4. **IF** $e_{line,row} > 0$ **THEN**

4.1 $Num=2, ToCheck_1 = line, ToCheck_2 = row$

4.2 **WHILE** $Num > 0$ **DO**

4.2.1 $k = ToCheck_1$

4.2.2 Seek $e^{(lb)}_{k,ma\_lb} = \max\limits_{1\le i\le M,i\neq k}\left(e^{(lb)}_{k,i}\right)$, $e^{(rb)}_{k,ma\_rb} = \max\limits_{1\le i\le M,i\neq k}\left(e^{(rb)}_{k,i}\right)$

4.2.3 **IF** $\left|e^{(lb)}_{k,ma\_lb} - e^{(rb)}_{k,ma\_rb}\right| < \varepsilon * 2$ **OR** $e^{(lb)}_{k,ma\_lb} - e^{(rb)}_{k,ma\_rb} > 0, x_{\max} - x_k < \varepsilon$ **OR** $e^{(lb)}_{k,ma\_lb} - e^{(rb)}_{k,ma\_rb} < 0, x_k - x_{\min} < \varepsilon$ **DO**

/* x_k cannot be adjusted*/

$AdjR_k = false, Num--$

$ToCheck_i = ToCheck_{i+1}, i=1...M-1$

$ToCheck_M = -1$

4.2.4 **IF** $AdjR_{ma\_lb} == true$

DO $ToCheck_{Num+1} = ma\_lb, Num++$

4.2.5 **IF** $AdjR_{ma\_rb} == true$

DO $ToCheck_{Num+1} = ma\_rb, Num++$

5. **ELSE** $x_k = x_k + \dfrac{e^{(lb)}_{k,ma\_lb} - e^{(rb)}_{k,ma\_rb}}{2}$, **GOTO** 2).

6. **STOP** // $Num \le 0$

7. **End**

5. Simulations and Conclusions

WMNE-MGME is an extension of WMNE-ME[3] which is a point-value emulation problem. The core idea of WMNE-MGME is to consider the interval equivalent character of wireless communication and to introduce the interval equivalent functions of path loss $f_{lb}(\overline{PL})$, $f_{rb}(\overline{PL})$ to formulate the emulation problem. In this section, we use simulations to evaluate the promotion of the probability of successful emulation.

In the simulations, the fixed wireless test-bed topology is shown in Fig. 2, and the separation distance between the two nodes connected with broken line is 60m. The 7-node fixed test-bed is composed of No. 1…7 nodes, and the 9from12-node fixed test-bed is a 9-node test-bed which is composed of No. 1…8 and No. 12 nodes. We use the 7-node and 9from12-node fixed test-bed to emulate 5-nodes user-defined wireless multi-hop network. In the same simulation, 1000 5-node wireless multi-hop networks are randomly produced. There are 1000 MinGenMax errors when emulate these 1000 networks in the fixed text-bed. The cumulative distributed function curve of these MinGenMax errors approximately shows the relationship of the probability of successful solution for WMNE-MGME and the user error-requirements.

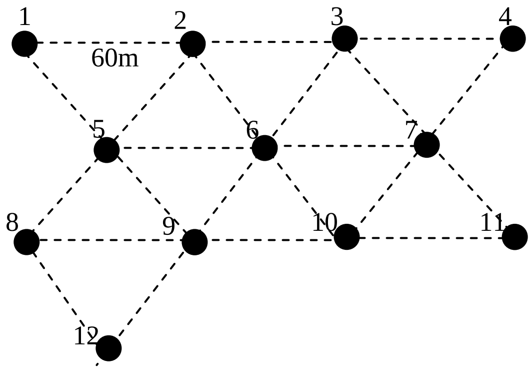

Fig2. The fixed wireless testbed in our simulations

According to the path loss model of wireless channel [5], the pass loss and the distance of a wireless link can be transformed to each other. In our simulations, we use interval equivalent functions of distance

$$f_{lb}(d)=\begin{cases} 0.1, d\in[0,80] \\ d, d\in(80,300) \\ 300, d\in[300,\infty) \end{cases} \quad f_{rb}(d)=\begin{cases} 80, d\in[0,80] \\ d, d\in(80,300) \\ 3000, d\in[300,\infty) \end{cases},$$

and the path loss exponent $\mu = 2.0$, the upper and lower bound of adjustable scale of attenuators are $x_{\min} = 0$, $x_{\max} = 70$

Fig. 3 shows the cumulative distributed curves of GenMax errors of interval equivalent emulation and Max errors of point-value emulation.

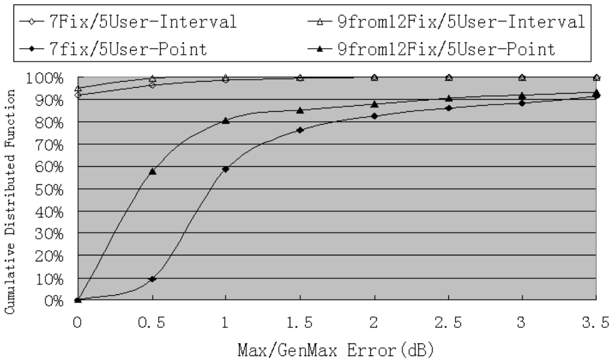

Fig 3. Comparation of point-value emulation and interval equivalent emulation

The above Fig. 3 shows that, after considering the interval equivalent of wireless communication, the probability of successful solution for wireless multi-hop networks scenario emulation obtained significant promotion. If we do point-value emulation, the probability of successfully emulating 5-node networks in the given 7-node, 9from12-node fixed testbed are both 0% when the user error-requirement is $0dB$, and the probability of successfully emulating 5-node networks in the given 7-node, 9from12-node fixed test-bed are 82.4%, 87.9% respectively when the user error-requirement is $2dB$. If we do interval equivalent emulation, the probability of successfully emulating 5-node networks in the given 7-node, 9from12-node fixed testbed are 92%, 94.9% respectively when the user error-requirement is $0dB$, and the probability of successfully emulating 5-node networks in the given 7-node, 9from12-node fixed test-bed are both 100% when the user error-requirement is $2dB$.

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