

Distributed Routing Based on Minimum End-to-End Delay for OFDMA Backhaul Mobile Mesh Networks

Jong-Moon Chung, Daeyoung Lee, Jong-Hong Park, Kwangjae Lim,
HyunJae Kim, and Dong-Seung Kwon

In this paper, an orthogonal frequency division multiple access (OFDMA)-based minimum end-to-end delay (MED) distributed routing scheme for mobile backhaul wireless mesh networks is proposed. The proposed scheme selects routing paths based on OFDMA subcarrier synchronization control, subcarrier availability, and delay. In the proposed scheme, OFDMA is used to transmit frames between mesh routers using type-I hybrid automatic repeat request over multipath Rayleigh fading channels. Compared with other distributed routing algorithms, such as most forward within radius R, farthest neighbor routing, nearest neighbor routing, and nearest with forwarding progress, simulation results show that the proposed MED routing can reduce end-to-end delay and support highly reliable routing using only local information of neighbor nodes.

Keywords: Wireless mesh network (WMN), OFDMA, backhaul, minimum end-to-end delay (MED), distributed routing.

I. Introduction

Wireless mesh networks (WMNs) allow significant flexibility in network architecture and provide benefits, namely, low upfront network setup cost, easy network maintenance, robustness, and reliable service coverage. For these reasons, WMNs can be applied in various service applications and are expected to play an essential role in next-generation wireless networking [1]. WMNs commonly allow multiple routing paths between communicating nodes and alternative routing paths can therefore be used if the original path's performance degrades, thereby enhancing the reliability of routing connectivity.

Orthogonal frequency division multiple access (OFDMA) transmission enables high frequency utilization and is very effective in broadband transmission. The most common application of OFDMA is found in mobile communication systems supporting shared multiuser uplinks and downlinks, in which groups of subcarriers are assigned to individual users. WMNs have two types of mesh nodes, that is, mesh routers (MRs) and mesh clients (MCs), wherein MRs form the backhaul WMN, and each MC wirelessly connects to a local MR, as shown in Fig. 1. In this paper, it is assumed that the WMN is composed of a large number of mobile MRs and MCs. Commonly, one or more MR will serve as a gateway to the Internet or another wired or wireless network, and the OFDMA WMN system has coverage up to 100 km (optimal performance up to 5 km) and supports reliable communications between mobile nodes up to 120 km/h (connectivity up to 350 km/h) [2]. To enable fast route adaptation under highly mobile conditions, a reliable and distributed routing mechanism is needed, for which purpose

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Jong-Moon Chung (phone: +82 2 2123 5863, jmc@yonsei.ac.kr), Daeyoung Lee (leedy@yonsei.ac.kr), and Jong-Hong Park (jhwannabe@yonsei.ac.kr) are with the School of Electrical & Electronic Engineering, Yonsei University, Seoul, Rep. of Korea.

Kwangjae Lim (kjlim@etri.re.kr) and Dong-Seung Kwon (dskwon@etri.re.kr) are with the Communications & Internet Research Laboratory, ETRI, Daejeon, Rep. of Korea.

HyunJae Kim (khjgo@etri.re.kr) is with the Creative Future Research Laboratory, ETRI, Daejeon, Rep. of Korea.

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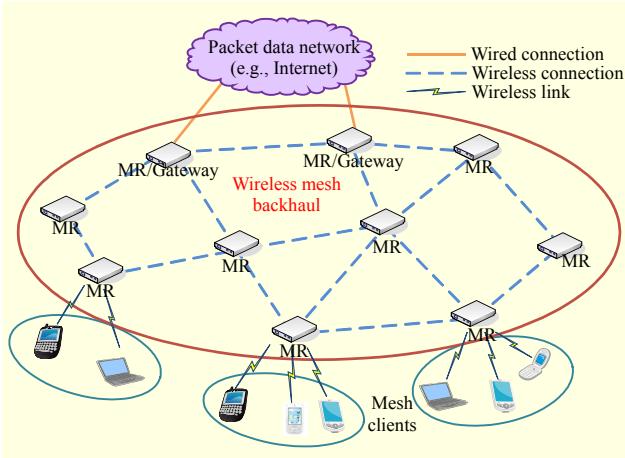


Fig. 1. WMN consisting of MRs and MCs.

the proposed minimum end-to-end delay (MED) routing protocol is presented.

In recent years, several papers have focused on OFDMA WMNs and multihop networking. In [3], a multichannel time division multiple access (TDMA) algorithm for channel and time slot allocation based on the length of flow to reduce delay over multihop WMNs was proposed. In [4], it was demonstrated that the influence of shadowing on channel capacity is more substantial than that of multipath fading, and a combined macroscopic selection diversity (MSD) and MIMO transmission scheme was therefore proposed to overcome the composite fading effects. In [5], the authors proposed a greedy algorithm to solve scheduling and resource allocation problems for OFDMA-based WMNs in a distributed manner and proposed a heuristic algorithm for fast execution of the scheduling scheme at each MR. As described above, existing papers on OFDMA mesh networks have focused on improving the physical layer (PHY) and medium access control (MAC) layer for scheduling and resource allocation; however, there is no paper that provides an optimal routing scheme considering the effects of OFDMA subcarrier synchronization and subcarrier availability in addition to end-to-end delay.

When a WMN is used as a backhaul/backbone network, its end-to-end delay performance over the routing path becomes very important, especially for real-time voice and multimedia services, as well as for military on-the-move (OTM) mission command and control (C2) applications.¹⁾ Therefore, in this paper, an MED routing algorithm for OFDMA WMNs is proposed. The proposed OFDMA WMN MED scheme must include the following two factors in next-hop MR selection to achieve optimized OFDMA multihop connectivity. First, an

MR of the backhaul WMN can only accept transmissions in which the difference in arrival time of the frames is within the OFDMA cyclic prefix (CP) decodable range. This OFDMA multiuser subcarrier synchronization requirement must be satisfied for proper demodulation. Second, all nodes of the selected routing path need to have sufficient availability in OFDMA frequency subcarriers to properly accommodate the service data rate. Other desirable functional characteristics of the MED scheme are a distributed route setup and adaptive reconfiguration. For a WMN supporting a large number of mobile MCs and MRs, distributed routing would be preferable since information collection of numerous MRs over a large scale backhaul WMN (that is, an area of tens to hundreds of km²) would be very time consuming and require significant overhead.

Distributed routing refers to a routing scheme in which next-hop node selection is performed by each node rather than performed by one node of the WMN in a centralized route selection process. A representative distributed local-information-based routing scheme is geographic routing. In general, the end-to-end time delay is proportional to the number of hops of the routing path. Therefore, to reduce end-to-end delay, geographic routing schemes (and related schemes) aim to reduce the total number of hops between source and destination. Representative geographic routing algorithms include most forward within radius R (MFR) [6] and farthest neighbor routing (FNR) [7], which are algorithms that attempt to reduce the total number of hops. However, as MFR and FNR attempt to configure routing paths with the minimum number of hops, they use maximum length hops, which results in poor signal-to-interference-plus-noise ratio (SINR) performances. Therefore, nearest with forwarding progress (NFP) [6] and nearest neighbor routing (NNR) [7] were proposed to maximize the SINR performance of each hop. However, NFP and NNR require many more hops to reach the destination compared with MFR and FNR. The end-to-end delay performance is determined by both the SINR of each hop (which influences the end-to-end throughput) and the number of hops (since queuing delay and multiplexing/multiple-access delay occurs at each MR). Therefore, in this paper, we investigate OFDMA scheduled access applied in mobile backhaul WMNs and propose an MED distributed routing algorithm customized for OFDMA multihop transmission over mobile WMNs, which has not been investigated in former papers.

The remainder of this paper is organized as follows. First, the SINR and multihop delay for OFDMA WMNs is analyzed. Next, the MED routing algorithm is proposed. Thereafter, the results for MED routing are presented and compared with the distributed routing algorithms MFR, NFP, FNR, and NNR.

1) The proposed MED scheme was developed to serve military tactical mobile communications OTM WMN applications.

Lastly, conclusions are drawn and future work is discussed.

II. OFDMA-Based MED Routing

1. End-to-End Delay Analysis for OFDMA WMNs

In the mobile backhaul WMN model, we assume K_{net} MRs share a W -Hz common bandwidth with N OFDMA orthogonal carriers. We define the OFDMA transmission signal between MRs i and j as

$$s_{ij}(t) = A(t) \sum_{z=-\infty}^{\infty} \sum_{l=0}^{N+N_g-1} B_{ij,l}^{[z]} p(t - lT_s - z(T + T_g)), \quad (1)$$

where $A(t)$ is the signal amplitude at time t , T_s is the sampling time, T is the OFDMA symbol time, T_g is the CP time, $B_{ij,l}^{[z]}$ indicates the transmitted IFFT (inverse fast Fourier transform) block, $N = T/T_s$, and $N_g = T_g/T_s$. The signal transmitted through the multipath Rayleigh fading channel is represented as

$$h_{ij}(t) = d_{ij}^{-\beta/2} \sum_{c=0}^{C-1} g_{ij,c} \delta(t - \frac{d_{ij}}{v} - \tau_{ij,c}), \quad (2)$$

where C is the number of multipaths, β is the path loss exponent, v is the speed of the signal, d_{ij} is the distance between MRs i and j , $\tau_{ij,c}$ is the multipath delay, and $g_{ij,c}$ is the channel gain, which is an independent and identically distributed complex Gaussian random variable with zero mean and variance $\gamma_c = \mathbb{E}|g_{ij,c}|^2$ and $\sum_{c=0}^{C-1} \gamma_c = 1$ [8], and $\delta(x)$ represents a delta function, where $\delta(x) = 1$ for $x = 0$ and 0 otherwise.

In OFDMA backhaul WMNs, several MRs can simultaneously transmit data packets to another MR because OFDMA enables multiple user access by assigning different subcarriers to different users. Therefore, the received signal at an MR can be expressed as a sum of received signals from all adjacent MRs located within the maximum interference range D_I . The received OFDMA signal at the receiver is demodulated using FFT (fast Fourier transformation) after the sampling process. The CP is used to eliminate the effect of multipath interference in the OFDMA signal, especially multipath interference that arrives later than the reference signal. However, the CP cannot eliminate interference that arrives before the reference signal. The OFDMA receiver system model of this paper assumes use of dynamic FFT positioning [8] to eliminate all multipath interference. Using the propagation time information of signals from the transmitter,

the receiver is able to control the position of the FFT window using dynamic FFT positioning. This controllable FFT window position can be represented as

$$T_w = \frac{D - d_{ij}}{v} + \tau_{\max}, \quad (3)$$

where D is the maximum one-hop transmission range and τ_{\max} is the maximum multipath delay. Commonly, $T_w > T_g$; therefore, the CP time T_g is represented as

$$\begin{aligned} T_g &= \max_{d_{ij}} (T_w) \\ &= \max_{d_{ij}} \left\{ (D - d_{ij}) / v + \tau_{\max} \right\} \\ &= D / v + \tau_{\max}. \end{aligned} \quad (4)$$

The maximum one-hop transmission range D can be determined from the CP time:

$$D = (T_g - \tau_{\max}) v. \quad (5)$$

For a reference MR, any MR in distance D can be guaranteed the minimum SINR γ_{\min} quality level; therefore, the relation $d_{ij} < D$ indicates that the one-hop transmission between MRs i and j can be achieved reliably. Commonly, the maximum one-hop transmission range D is smaller than the interference range D_I [9], where $D < d_{ij} < D_I$ is the range of d_{ij} in which MR i 's signal is not sufficient to conduct reliable communications but is detected as interference affecting MR j . Based on the configuration of the transmission signal and the wireless channel condition, using (5), the maximum interference range for MR j ($D_{I,j}$) to guarantee γ_{\min} with maximum transmission range D can be derived as shown in (6), where $K_{D_{I,j}}$ is the number of MRs within interference region $D_{I,j}$, G_m is the frequency domain channel gain at the m -th subcarrier, \mathcal{A}_k is the set of subcarriers allocated to MR k , $\tau_{kj,c} = c\tau_{\max}/(C-1)$, and $E_s = A(t)^2 D_{I,j}^{-\beta} T_s$. In addition, $b_{k,n}^-$ and $b_{k,n}^+$ represent two consecutive symbols of subcarrier n .

Moreover, $\mathcal{G}(p, y)$ represents the residual interference after FFT processing at the receiver, where $N_w = T_w / T_s$, and $A \bmod B$ represents the modulo value of A in reference to B . The first and third terms of (7) indicate the multiuser interference from other MRs that can be completely eliminated, and the second term indicates the residual interference that cannot be eliminated by the dynamic FFT window. Based on this system model, we can evaluate the cumulative distribution function (CDF) $\Pr(\gamma_{ij} \geq z)$ of the received SINR at MR j γ_{ij} [8].

$$D_{I,j} = \frac{DN_0}{E_s^{\beta} \left\{ \frac{|G_m|^2}{\gamma_{\min}} - \sum_{k=1}^{K_{D_{I,j}}} \left(\frac{d_{kj}}{D} \right)^{-\beta} |G_{kj,m}|^2 \sum_{c=0}^{C-1} \gamma_c \left| \sum_{n \in \mathcal{A}_k} (b_{k,n}^- - b_{k,n}^+) \mathcal{G} \left(n - m, \frac{d_{kj} - D}{v} + \tau_{kj,c} \right) \right|^2 \right\}^{\frac{1}{\beta}}}. \quad (6)$$

$$\mathcal{G}(p, y) = \begin{cases} 0, & 0 < y \bmod (T + T_g) \leq T_w, \\ \frac{\sin\left(\pi\left(\left\lfloor \frac{y \bmod (T + T_g)}{T_s} \right\rfloor - N_w\right)N\right)}{N \sin\left(\frac{\pi p}{N}\right)} e^{j \frac{\pi p}{N} \left(\left\lfloor \frac{y \bmod (T + T_g)}{T_s} \right\rfloor + N_w - 1\right)}, & T_w < y \bmod (T + T_g) \leq T_w + T, \\ 0, & T_w + T < y \bmod (T + T_g) \leq T_g + T. \end{cases} \quad (7)$$

The authors in [10] proposed a cross-layer design to obtain the packet error rate (PER) when considering adaptive modulation and coding for hybrid automatic repeat request (HARQ) systems, where the average PER for a multipath Rayleigh fading channel is expressed as

$$P_{p,ij} = \int_0^\infty PER_{ij}^n(z) \frac{\partial}{\partial z} \Pr(\gamma_{ij} \leq z) dz, \quad (8)$$

where $PER_{ij}^n(z) \approx \min(1, a_n e^{-g_n z})$, $a_n \in \{2.5, 1.8, 3.1, 1.5\}$, and $g_n \in \{1.0, 0.4, 0.3, 0.1\}$ for transmission mode $n = 1, 2, 3, 4$, in which modes 1 and 2 use QPSK, and modes 3 and 4 use 16-QAM. Modes 1 and 3 use a 1/2 code rate, modes 2 and 4 use a 2/3 code rate, and $\partial \Pr(\gamma_{ij} \leq z) / \partial z$ is the probability density function of the received SINR based on the CDF of the received SINR $\Pr(\gamma_{ij} \leq z)$.

In this paper, we use the type-I HARQ as the retransmission scheme, but do not apply limits of retransmission. Therefore, the average number of transmissions for successful transmission becomes

$$N_{ij}^{\text{tr}} = \sum_{k=1}^{\infty} k P_{p,ij}^{k-1} (1 - P_{p,ij}) = \frac{1}{1 - P_{p,ij}}. \quad (9)$$

From the average number of transmissions, a one-hop delay for successful transmission can be expressed as

$$T_{ij}^{\text{h}} = T_f N_{ij}^{\text{tr}}, \quad (10)$$

where T_f is the OFDMA frame duration during which frames are sent synchronously using time division duplex frames.

For a routing path \mathbb{P} (that is, the set of intermediate MRs), the multihop end-to-end delay can be obtained from

$$T_{\text{ete}} = \sum_{i=1}^{|\mathbb{P}|} T_{\mathbb{P}(i), \mathbb{P}(i+1)}^{\text{h}}, \quad (11)$$

where $|\mathbb{P}|$ is the length of set \mathbb{P} , $\mathbb{P}(i)$ is the i -th element of set \mathbb{P} , and $T_{\mathbb{P}(i), \mathbb{P}(i+1)}^{\text{h}}$ is the single-hop delay between nodes $\mathbb{P}(i)$ and $\mathbb{P}(i+1)$.

$$N_{ij}^{\text{tr}}(d_{ij}) = \frac{1}{1 - \int_0^\infty PER_{ij}^n(z) \cdot \frac{\partial}{\partial z} \left[1 - \exp \left\{ -z \left(\sum_{k=1}^{K_{D_{I,j}}} \left(\frac{d_{kj}}{d_{ij}} \right)^{-\beta} \sum_{c=0}^{C-1} \gamma_c \left| \sum_{n \in \mathcal{A}_k} (b_{k,n}^- - b_{k,n}^+) \mathcal{G} \left(n - m, \frac{d_{kj} - d_{ij}}{v} + \tau_{k,c} \right) \right|^2 + \frac{N_0 D_{I,j}^{-\beta}}{E_s d_{ij}^{-\beta}} \right\} \right] dz} \quad (12)$$

2. MED Routing Scheme

The objective of the proposed distributed MED routing scheme is to select the optimal MRs that minimize the end-to-end delay (T_{ete}) for a routing path \mathbb{P} . Optimal selection of MRs for the routing path is based on the OFDMA subcarrier synchronization, subcarrier availability, and the time-delay metrics. In the proposed system, each MR is highly mobile and synchronization among the mobile nodes is based on the arrival time of the OFDMA frame received from the communicating MR. The system also attempts to minimize interference among MRs by limiting the transmission distance among one-hop MRs of a routing path. The OFDMA multiuser signal reception at a specific MR requires all connecting nodes to be within a distance that does not exceed the maximum transmission range D , such that the OFDMA signals from multiple MRs are received within the synchronized decodable range. In addition, the receiving MR must have sufficient OFDMA subcarrier availability to accommodate the requested data rate. Therefore, the optimization statement becomes

$$\text{Minimize } T_{\text{ete}}(\mathbb{P})$$

$$\text{Subject to } d_{\mathbb{P}(i), \mathbb{P}(i+1)} \leq D, \quad \forall i$$

$$\mathbb{L}_{\mathbb{P}(i)} = \{l : d_{\mathbb{P}(i), l} \leq D_{I, \mathbb{P}(i)}\}, \quad \forall i,$$

$$N - \sum_{l \in \mathbb{L}_{\mathbb{P}(i)}} x_l \geq \overline{x}_R, \quad \forall i$$

$$\sum_{l \in \mathbb{L}_{\mathbb{P}(i)}} \sum_{k \in \mathbb{C}} x_l^k \leq 1, \quad \forall i,$$

where $\mathbb{L}_{\mathbb{P}(i)}$ is the set of nodes within interference range $D_{I, \mathbb{P}(i)}$ of the current routing node $\mathbb{P}(i)$, x_l is the number of subcarriers used by node l , \overline{x}_R is the required number of subcarriers for MR transmission, \mathbb{C} is the set of subcarriers, and $x_l^k = 1$ if node l uses subcarrier k , otherwise $x_l^k = 0$. The first

constraint requires that each hop distance of the routing path \mathbb{P} not exceed the maximum routing distance D . The second constraint defines $\mathbb{L}_{\mathbb{P}(i)}$. The third constraint requires all MRs of the routing path \mathbb{P} to support a minimum of x_R subcarriers for packet transmission for the given path. The last constraint prevents duplicated usage of subcarriers from occurring within interference range $D_{I,\mathbb{P}(i)}$.

$\Pr(\gamma_{ij} \geq z)$ is also a function of the distance between MRs. Commonly, the SINR degrades as the transmission distance increases, and, in related terms, $P_{p,j}$ and N_{ij}^{tr} become worse as the transmission distance increases. Therefore, the average number of transmissions N_{ij}^{tr} can be expressed as a function of the distance between MRs (that is, d_{ij}), as presented in (12).

The MED routing path is formed using the following approach. For reference of the routing path, a source-to-destination straight line (that has a length of d_{ete}) is used. The lower bound of the number of hops is d_{ete} / d_h , where d_h is the one-hop routing distance. Using (10) and (12), the end-to-end delay can be expressed as a function of the one-hop routing distance $d_{ij} = d_h$.

$$T_{\text{ete}}(d_h) = \frac{T_f N_{ij}^{\text{tr}}(d_h) d_{\text{ete}}}{d_h}. \quad (13)$$

The single-hop transmission distance $d_{h,\min}$ (which is constrained by $d_{h,\min} \leq D$) that minimizes the end-to-end delay $T_{\text{ete}}(d_h)$ can be obtained from

$$\left. \frac{\partial T_{\text{ete}}(d_h)}{\partial d_h} \right|_{d_h=d_{h,\min}} = 0, \quad (14)$$

which means that $T_{\text{ete}}(d_h)$ results in an extreme value (local minimum) when $d_h = d_{h,\min}$.

Figure 2 shows a scenario for MR selection of the MED routing scheme. In the MED routing scheme, the same assumption used in distributed geographic routing [7] schemes is assumed, wherein each node is assumed to be able to acquire its own location, locations of neighboring nodes, and the location of the destination node by way of exchanging location information. In addition, the location information of the destination node is forwarded to all intermediate nodes that are included in the routing path [7]. The proposed MED routing scheme is operated based on a distributed manner, and therefore requires the location information of the one-hop neighboring MRs and the location information of the source and destination MRs to enable selection of the next MR for each hop.

Using this information, the MED scheme first computes a point on the line l_{sd} , which is the line between the source and destination MRs. The source-to-destination vector $v_{sd} = p_d - p_s$, where p_s and p_d are vectors indicating the location of the source and destination, respectively, and the location vector of the

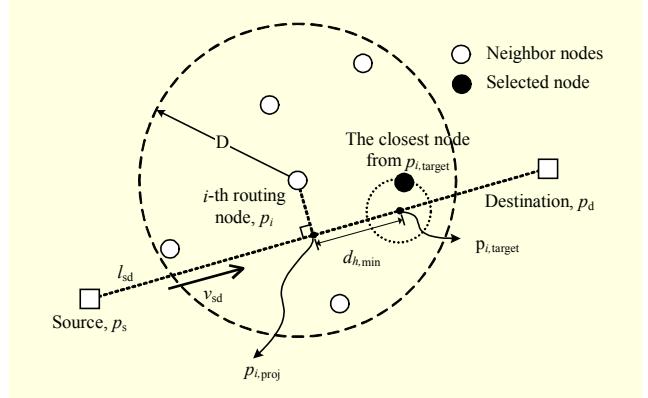


Fig. 2. MED MR selection scenario.

i -th MR is p_i ($\{p_s, p_d, p_i\} \in \mathbb{R}^2$ for $\forall i$). The proposed MED routing scheme uses the following three steps in finding the next-hop MR of the routing path.

Step 1. Find the point $p_{i,\text{proj}}$ that satisfies the equations $v_{sd} \cdot (p_i - p_{i,\text{proj}}) = 0$ and $\det[v_{sd}, p_{i,\text{proj}} - p_s] = 0$ subjected to $|p_{i,\text{proj}} - p_i| \leq D$.

In Step 1, $A \cdot B$ indicates an inner product of row vectors A and B , and $\det[A, B]$ indicates the determinant of matrix $[A, B]$. The matrix $[A, B]$ is a 2×2 square matrix because both A and B are 2×1 row vectors. From the first equation, we find that a location vector $p_{i,\text{proj}}$ satisfies the inner product equation. In the 2×2 square matrix case, an absolute value of the determinant is the area of the parallelogram formed by the row vectors included in the 2×2 square matrix. Therefore, the second equation refers to the condition of the two vectors v_{sd} and $p_{i,\text{proj}} - p_s$ being parallel. Through solving these two equations, one can find the point $p_{i,\text{proj}}$ that is the projection point of the i -th routing node on the line l_{sd} .

Step 2. Find a target point $p_{i,\text{target}} = p_{i,\text{proj}} + d_{h,\min} \frac{v_{sd}}{|v_{sd}|}$ subjected to $|p_{i,\text{target}} - p_i| \leq D$.

The target point $p_{i,\text{target}}$ is $d_{h,\min}$ away from the point $p_{i,\text{proj}}$ on line l_{sd} in the direction of the destination node.

Step 3. Among the unselected MRs, select the closest MR (to be denoted as j^*) from $p_{i,\text{target}}$ as the next routing node among neighbor nodes that satisfy two conditions, $N - \sum_{l \in \mathbb{L}_j} x_l \geq \bar{x}_R$ and $\sum_{l \in \mathbb{L}_j} \sum_{k \in C} x_l^k \leq 1$, where $\mathbb{L}_j = \{l : d_{j,l} \leq D_{I,j}\}$ and $j^* = \arg \min_{j \in \mathbb{N}_i} (|p_j - p_{i,\text{target}}|)$.

\mathbb{N}_i is the set of the i -th MR's neighbors that are located within radius D from the i -th MR and satisfy the condition $N - \sum_{l \in \mathbb{L}_j} x_l \geq \bar{x}_R$, p_j is the location of the j -th MR that is a neighbor MR of the i -th MR, and j^* indicates the selected MR through the MED routing node selection.

The MED routing algorithm pseudocode presented in

Algorithm 1 is based on these three steps.

Algorithm 1: MED Routing

- 1: Input: Source node n_s , Destination node n_d, p_s, p_d .
- 2: Begin:
- 3: Setup and initialize:
 $i=1, \mathbb{P} = \{n_s\}, d_{ete} = |p_d - p_s|$
- 4: While
- 5: Find the target point $p_{i,target}$ through Steps 1 and 2.
- 6: Select the next routing node j^* through Step 3.
- 7: Update

$$\begin{cases} d_{sj^*} = |p_{j^*,proj} - p_s|, \\ i = i + 1. \end{cases}$$
- 8: If $d_{sj^*} < d_{ete}$: $\mathbb{P}(i) = j^*$ and go to ‘While’.
else : $\mathbb{P}(i) = n_d$ and go to ‘End while’.
- 9: End while

III. Simulation Results

In this section, the Matlab simulation performance of the proposed MED routing scheme is compared to the performances of other distributed routing algorithms (that is, MFR, FNR, NNR, and NFP) based on the same OFDMA backhaul WMN conditions of $W = 10$ MHz, $D_I = 3,000$ m, $N = 256$, $\beta = 2$, $E_s/N_0 = 1$, $C = 10$, $T = 25$ μ s, $T_g = T/3$, and $T_f = 5$ ms.

Figure 3 presents the average end-to-end delay of simulated routing algorithms according to node density based on a fixed required number of subcarriers per MR transmission ($x_R = 5$ subcarriers). In the simulation experiments, a larger node density results in a shorter average source-to-destination distance d_{ete} . Generally, the end-to-end delay of all routing schemes increases as d_{ete} increases. When compared to the distributed routing schemes of MFR, FNR, NNR, and NFP, the proposed MED routing scheme shows a significant performance gain as the node density exceeds 1.2 nodes/km². For example, at the 4 nodes/km² node density level, MFR, FNR, NNR, and NFP respectively result in a 42.2-ms, 58.4-ms, 82.1-ms, and 195.2-ms longer delay compared to the MED scheme’s performance. However, for low node density values below 1.2 nodes/km², the proposed MED scheme does not result in the best end-to-end delay performance among the simulated routing algorithms. The proposed MED scheme performs best when one or more of the MRs are located in the vicinity of the target point $p_{i,target}$. In a low node density network, the number of MRs close to the target point $p_{i,target}$ is small, and, therefore, the selected MR (by the proposed MED scheme) will not always result in a desirable performance.

Regarding *success probability*, the distributed routing schemes are compared in Fig. 4. “Success probability” refers to

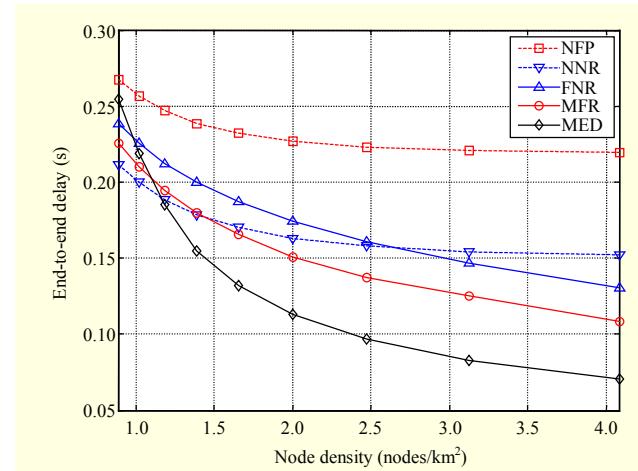


Fig. 3. End-to-end delay with varying node density.

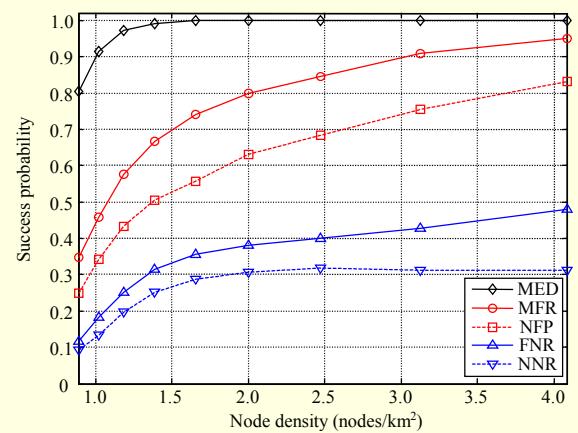


Fig. 4. Success probability with varying node density.

the probability of successfully establishing a routing path from the source to the destination, while satisfying all OFDMA subcarrier availability and synchronization requirements. Figure 4 shows that MFR, NFP, FNR, and NNR result in a significantly lower success probability than the MED scheme for all node density values in the range of interest. For example, at the 2 nodes/km² node density level, MFR, NFP, FNR, and NNR respectively result in only 79.9%, 63.2%, 38.2%, and 30.1% compared to the MED scheme’s performance, which reaches 100% success probability. This results from the fact that MFR, NFP, FNR, and NNR select the farthest or the nearest next-hop MR within a one-hop transmission range. The MED scheme calculates the target point $p_{i,target}$ on the line l_{sd} and selects the closest MR as the next routing node among candidate MRs and can therefore achieve the best accessibility to the destination MR for a significantly wider range of node densities.

Figure 5 presents the success probability of the distributed routing schemes for a different required number of subcarriers

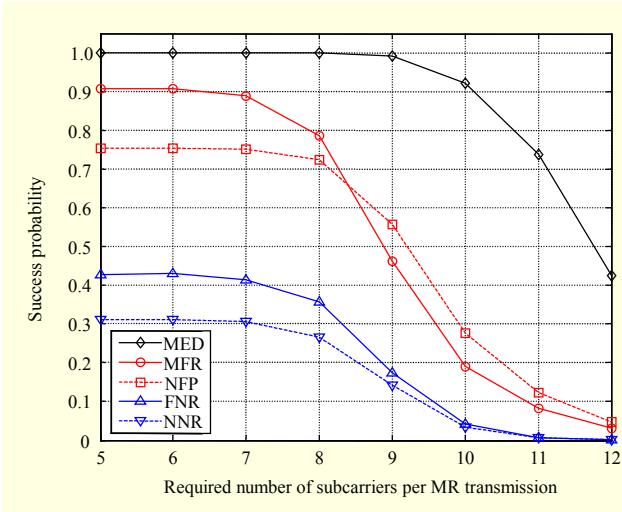


Fig. 5. Success probability with varying required number of subcarriers.

per MR transmission based on $d_{\text{ete}} = 10$ km. A larger required number of subcarriers per MR transmission results in a higher traffic load on the backhaul WMN. Figure 5 shows that the proposed MED performs significantly better than the other distributed routing schemes, where all schemes maintain a certain level of success probability up to a certain required number of subcarriers per MR transmission point and then the performance degrades beyond that point. Performance degradation results from not being able to support sufficient OFDMA subcarrier availability compared to the generated traffic demand.

IV. Conclusion & Future Work

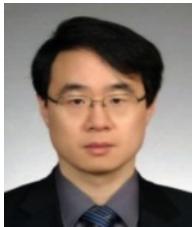
In this paper, a minimum end-to-end delay (MED) distributed routing scheme for OFDMA backhaul mobile WMNs was proposed. The routing algorithm selects MRs of the routing path to accomplish minimum end-to-end time delay while supporting OFDMA subcarrier availability and synchronization controllability. Simulation results show that the proposed MED routing scheme provides the smallest end-to-end delay and also a significantly higher end-to-end accessibility probability compared with the distributed routing algorithms MFR, FNR, NNR, and NFP.

Work is in progress to develop ways to support seamless interoperability and maximum accessibility for backhaul WMNs based on a heterogeneous access protocol [11], [12].

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Jong-Moon Chung has been a professor in the School of Electrical and Electronic Engineering and the director of the Communications & Networking Laboratory (CNL) at Yonsei University, Seoul, Rep. of Korea, since 2005. Formerly, he was an assistant professor in the Department of Electrical Engineering at Pennsylvania State University, University Park, PA, USA, after which he was a tenured associate professor in the School of Electrical and Computer Engineering at Oklahoma State University, Stillwater, OK, USA. He received his PhD in electrical engineering from Pennsylvania State University, University Park, PA, USA, in 1999. He is currently an editor of the *IEEE Transactions on Vehicular Technology*. His research

is in the areas of robotics, mobile technology, satellite technology, ad-hoc networks, future Internet, and broadband QoS networking.



Daeyoung Lee received his BS from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Rep. of Korea, in 2008. He worked on the project of internetworking technology for LTE and mobile WiMAX as a research member in the Communications & Networking Laboratory (CNL), directed by Dr. Jong-Moon Chung. He is currently a graduate student in the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Rep. of Korea. His research is in the areas of wireless mesh networks (WMNs) and internetworking technology between heterogeneous networks.



Jong-Hong Park received his BS from the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Rep. of Korea, in 2010. He worked on the project of scheduling and routing for OFDMA wireless mesh networks (WMNs). He is currently a graduate student in the School of Electrical and Electronic Engineering, Yonsei University, Seoul, Rep. of Korea. His research is in the areas of WMNs, mobile cloud computing, and future Internet.



Kwangjae Lim received his BS, MS, and PhD in electronics engineering from Inha University, Incheon, Rep. of Korea, in 1992, 1994, and 1999. In March 1999, he joined ETRI, Daejeon, Rep. of Korea. Since 1999, he has worked on the standardization of mobile and satellite communications. Since 2010, he has headed a mobile application team. His research interests are in mobile and wireless communications.



HyunJae Kim received his BS in 1998 from Inha University, Incheon, Rep. of Korea, and his MS in 2000 from Gwangju Institute of Science and Technology, Gwangju, Rep. of Korea. From 2000 to 2008, he worked on the development of the MAC S/W of WCDMA and the WiBro system, the WiBro advanced system, and the MMR system. He developed the SLS (System Level Simulator) for the TICN project in 2009. Since 2010, he has been developing the spec. and testbed system of WMNs. He is a senior researcher at ETRI, Daejeon, Rep. of Korea.



Dong-Seung Kwon joined ETRI, Daejeon, Rep. of Korea, in 1988, where he is currently an executive director and a principal member of the research staff. He received his MS and PhD in electrical engineering from Yonsei University, Seoul, Rep. of Korea, in 1987 and 2004, respectively. His current research interests include cellular mobile communication technology, mobile mesh networks, and device-to-device communication.