# Tier-based Proactive Path Selection Mode for Wireless Mesh Networks

**Zhang Fu-Quan, Inwhee Joe and Yong-Jin Park**
Department of Electronic and Computer Engineering,
Hanyang University, Seoul, 133-791, Korea
[e-mail: zhangfq@dsc.ac.kr, iwjoe@hanyang.ac.kr, yjp@hanyang.ac.kr]
*Corresponding author: Inwhee Joe

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## Abstract

In the draft of the IEEE 802.11s standard, a tree topology is established by the proactive tree-building mode of the Hybrid Wireless Mesh Protocol (HWMP). It is used for cases in which the root station (e.g., gateway) is an end point of the majority of the data connections. In the tree topology, the root or central stations (e.g., parent stations) are connected to the other stations (e.g., leaves) that are one level lower than the central station. Such mesh stations are likely to suffer heavily from contention in bottleneck links when the network has a high traffic load. Moreover, the dependence of the network on such stations is a point of vulnerability. A failure of the central station (e.g., a crash or simply going into sleep mode to save energy) can cripple the whole network in the tree topology. This causes performance degradation for end-to-end transmissions. In a connected mesh topology where the stations having two or more radio links between them are connected in such a way that if a failure subsists in any of the links, the other link could provide the redundancy to the network. We propose a scheme to utilize this characteristic by organizing the network into concentric tiers around the root mesh station. The tier structure facilitates path recovery and congestion control. The resulting mode is referred to as Tier-based Proactive Path Selection Mode (TPPSM). The performance of TPPSM is compared with the proactive tree mode of HWMP. Simulation results show that TPPSM has better performance.

***Keywords:*** Path selection mode, path recovery, routing, 802.11s

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## 1. Introduction

Emerging Wireless Mesh Network (WMN) technology aims at forming a self-organized wireless backbone and offering connectivity to end-users over multi-hop communication of large coverage areas. The ongoing 802.11s standardization specifies network establishment, administration and maintenance. This paper is based on the IEEE 802.11s draft version D5.0 [1] from April 2010. **Fig. 1** shows an example of the wireless mesh networks defined in IEEE 802.11s.

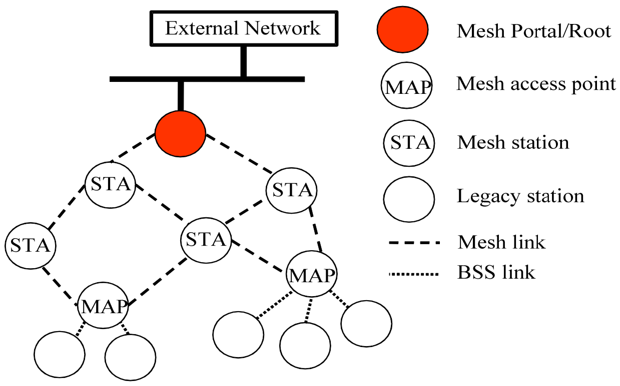



**Fig. 1.** The architecture of WMN

In IEEE 802.11s, primitive wireless relay nodes are referred to as mesh stations (Mesh STAs). Mesh STAs are able to automatically discover each other and establish a wireless backbone. A mesh portal is used for the Mesh STAs to communicate outside the mesh. A mesh access point (MAP) has all of the functionality of a Mesh STA and provides a BSS (Basic Service Set) to support communication with the legacy STA.

The proactive protocol Radio-Aware Optimized Link State Routing (RA-OLSR), which is extended from the early Optimized Link State Routing Protocol (OLSR) [2] was removed from the current draft of IEEE 802.11s. Only the Hybrid Wireless Mesh Protocol (HWMP) [3] is described as the default routing protocol in the draft. The HWMP is operated on layer 2 using MAC addresses, unlike the traditional routing protocols, which operate on layer 3 with IP addresses. HWMP can be configured to be purely reactive, or to combine the flexibility of on-demand path selection with a proactive path setup mode.

*On-demand mode*: The functionality of this mode is always available. It allows mesh STAs to communicate using peer-to-peer paths. It has some path discovery latency.

*Proactive path setup modes*: The HWMP specification considers two different approaches for proactive path setup towards root mesh stations: proactive Path Request (PREQ) mode and RANN mode.

The RANN mode uses special broadcast root announcement (RANN) messages, which periodically information on suitable next hops towards the root mesh station. The RANN messages, however, do not establish any paths. The actual path selection is done with unicast single-hop path requests and path replies based on the next hop information. In this paper, we focus on the proactive PREQ mode. The RANN mode has not been considered due to its peculiarity [4].

The proactive PREQ mode is used in cases in which a root station (e.g., gateway) is an end point of the majority of data connections. The root mesh station periodically broadcasts PREQ packets to all of the mesh stations in the network in order to construct and refresh a tree routing topology. Since this PREQ mode maintains paths from the root mesh station to every other mesh station in a proactive manner, the actual data communication between them can occur quickly. The combination of the reactive and proactive elements of HWMP enables efficient path selection in a wide variety of mesh networks. However, a central station is connected to the other stations (e.g., leaves) that are one level lower than the central station in the tree topology. The dependence of the entire network on one central station is a point of vulnerability. A failure of the central station (e.g., a crash or simply going into sleep mode to save energy) can cripple the whole network. Additionally, for a multiplicity of competing traffic flows, the central station may be the bottleneck of the branches and may suffer from contention and congestion, which may lead to communication failures. This causes performance degradation for end-to-end transmissions.

Overviews of HWMP and its evolution over time can be found in [3][5]. The path selection mode of HWMP has started to attract scientific analysis only recently: theoretically [6], by simulation analysis [4][7], and by implementation. The implementations published so far have not been suitable to perform a reasonable analysis of the different HWMP modes. They do not implement all of the necessary path discovery elements [8], are based on an older draft D1.07 [9], or diverge from the draft [10][11]. Error recovery for the proactive RANN mode is studied in [12]. In order to circumvent the initial latency of the reactive path setup, a combination of the reactive and proactive modes is proposed in [13]. Paper [14] uses cryptographic extensions to provide authenticity and integrity of the HWMP routing messages, and prevents unauthorized manipulation of mutable fields in the routing information elements. Paper [15] proposed a security mechanism to secure control message of HWMP. Paper [16] made simple modifications in the HWMP to incorporate smart antenna transmission scheme. For load balancing purposes, the algorithm in [17] can obtain flow rate information between routers by packet sampling. Paper [18] presented a method to achieve load balance by exchanging routing information between internet gateways.

In this paper, we proposed a tier-based path selection mode. This mode based on different aspects, such as by focusing on the link redundancy characteristic in the mesh network. In a connected mesh topology where the stations having two or more radio links between them are connected in such a way that if a failure subsists in any of the links, the other link could provide redundancy to the network. Parts of such local redundancy links are preserved in our path selection mode by organizing the network into concentric tiers around the root mesh station. This can be utilized to facilitate path recovery and to control congestion. Moreover, the proposed tier-based structure is extended from the underlying HWMP, and can be constructed at the same time as proactive tree construction of HWMP. By this, the tier-based path selection mode can be integrated with current 802.11s draft with a minimum modification.

The remainder of this paper is organized as follows. Section 2 presents the motivation behind the proposed mode. We develop the Tier-based Proactive Path Selection Mode (TPPSM) in Section 3. The simulation results are discussed in Section 4, and the conclusions are presented in Section 5.

## 2. Motivation

Our approach is better motivated with an example. Assume that the radio links of stations are initially formed as shown in **Fig. 2(a)** in a connected mesh topology in which the nodes have two or more links between them.

A tree topology **Fig. 2(b)** is established using the following steps of the proactive PREQ mode in HWMP.

Step 1: A root station periodically broadcasts a proactive PREQ with an incremental sequence number. HWMP uses the sequence numbers to prevent the creation of path loops and to distinguish stale and fresh path information.

Step 2: Intermediate stations respond to the PREQ. If no path to the root mesh station exists, a station that received a proactive PREQ creates a new one. Each mesh station may receive multiple copies of a proactive PREQ. A mesh station updates its current path to the root mesh STA if and only if the PREQ contains a greater HWMP sequence number, or if the HWMP sequence number is the same as the current path and the PREQ offers a better path metric than the current path to the root mesh STA. The station will update and broadcast the PREQ to its neighbors. HWMP is defined for operation with arbitrary path metrics, such as hop count or a radio-aware metric. The 802.11s draft standard, for example, specifies the airtime link metric as a radio-aware metric. In this paper, the traditional hop count has been used as the path link metric.

Step 3: A Path Reply (PREP) may be sent in response to a proactive PREQ. For the case in which the proactive path reply flag in the PREQ is set, the station shall send a proactive PREP. If the flag is not set, the station may send a proactive PREP if data communication is required. The latter is used in this paper, since it generates less overhead (about one-third of the overhead of the former) and is more attractive in all networks with a high traffic load [4].

Two issues may affect the performance of a proactive tree topology that is established under the above steps.

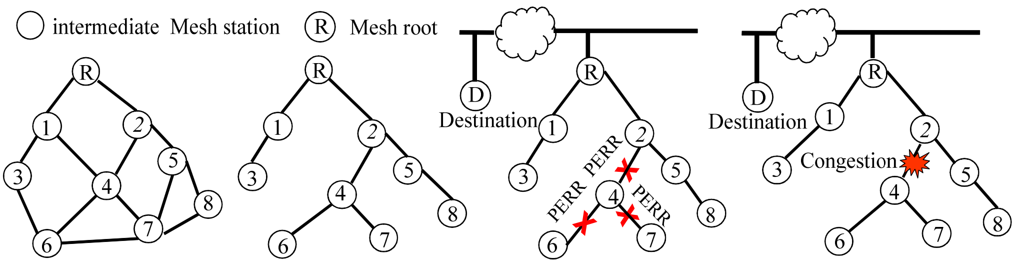



**Fig. 2.** Issues related to the proactive PREQ mode

*Path recovery issue:* When the mesh station determines that the link to the next hop of an active path in its forwarding information is no longer usable (**Fig. 2(c)**). A PERR (Path Error) element is generated and propagated by the mesh stations to announce the unreachable destination. The announcement is sent to all of the traffic sources that have a known active path to the destination. The related stations may have to buffer the data and delay the data transmission until the station gets a new path to forward the data.

*Congestion issue:* As shown in **Fig. 2(d)**, a parent station or a root may suffer congestion that is caused by the bottleneck effect when they relay most of the packets (e.g., the destination exists in the external network). In the congestion control mechanism of the draft, if congestion is detected, a congested station determines which nearby stations should be controlled and sends them a signaling message. The stations that received the signaling messages apply rate control until the congestion duration that was specified in the signaling message expires [1]. The draft does not specify the congestion detection rate control algorithms. Since the congestion duration is the only information that is contained in the signaling messages, the congested station only informs the controlled stations about the congestion. It is not able to consider the state of the controlled stations or to specify how to adjust the transmission rate.

The link redundancy characteristic (**Fig. 2(a)**) in mesh networks can be used for path recovery and to control congestion to some extent. Thus, questions about how to utilize the redundancy links to alleviate the above issues and to be compatible with the draft standard are the primary motivations behind our scheme.

## 3. Tier-based Proactive Path Selection Mode

This paper proposes a Tier-based Proactive Path Selection Mode (TPPSM) that organizes the network into tiers around the root station. It is based on the current draft standard with only minimal modifications. It is composed of two major processes: Tier Construction and the Active Phase. The formats of the control messages in these processes are mainly modified from the proactive tree-building mode of the HWMP protocol. We first describe the principle of the tier construction. Then we develop the TPPSM mode.

### 3.1 Principle of Tier Construction

The mesh stations themselves can form a tier structure by relaying a PREQ message. The format of the PREQ message is similar to the PREQ in 802.11s, but with an additional *tier-rank* field, which indicates the tier rank of the station that sent the message.

The following steps present the details of this process:

(1) The root station broadcasts a PREQ message. All stations that can successfully receive this message recognize that they belong to tier 1.

(2) Each station increments the tier-rank before forwarding the PREQ message.

(3) A station receiving a PREQ message with tier-rank n joins tier n, unless it already belongs to a tier of a lower rank.

A listing of the above steps is summarized in Algorithm 1. (A similar concept for constructing a tier structure was discussed in [19].)

Algorithm 1: Principle of tier construction algorithm

```
For each PREQ message arrival:
  if (tier-rank in the message is not larger than the tier-rank that already joined)
        join this tier
        increase the tier-rank
        broadcast the PREQ message
        record the neighbor who sent the message
  end if
```

### 3.2 Tier Construction

The tier structure can be constructed at the same time as proactive tree topology construction. The following steps present the details of this process:

*Step 1: A root station periodically broadcasts a proactive PREQ message.* A root station increases its sequence number and initializes the tier-rank as 1 when it broadcasts the PREQ.

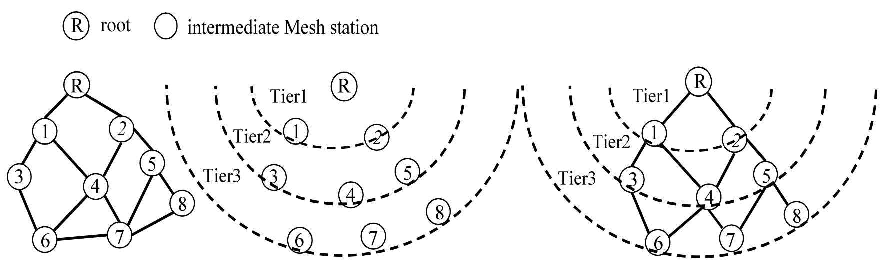
*Step 2: Intermediate stations respond to the PREQ.* If no path to the root mesh station exists, a station that received a proactive PREQ creates a new one. A station receiving a PREQ message with tier-rank n joins TIER n, unless it already belongs to a tier of lower rank. Each mesh station may receive multiple copies of a proactive PREQ. A mesh station updates its current path to the root mesh station if and only if the PREQ contains a greater HWMP sequence number, or the HWMP sequence number is the same as the current path and the PREQ offers a better path metric than the current path to the root mesh station, or the HWMP sequence number is the same as the current path and the tier-rank in the PREQ is not larger than the tier-rank that already joined. Then it increases the tier-rank and broadcasts the PREQ message.

*Step 3: The generation of PREP is the same as the generation of PREP in HWMP.*

A list of the above steps is summarized in Algorithm 2. After the steps are completed, not only is the tree topology constructed, but the entire network is also organized into tiers around the root station. As shown in **Fig. 3**, parts of the local redundancy links are preserved in the construction of the tier structure. This increases path robustness, and can be utilized to control congestion in the next active phase.

Algorithm 2: the process of simultaneous construction of tier structure and proactive tree topology

```
At a root station:
    for each root interval  do
        increase sequence number
        initialize tier-rank as 1
        broadcast a proactive PREQ
    end for
At an intermediate station:
    When a PREQ message arrives:
    if (the message has lower sequence number)
        drop it
    else if (no path to the root mesh station exists)
        create one
    else if ( the message indicates better path metric than current path)
        update current path to the root mesh
    else if (tier-rank in the message is not larger than the tier-rank that already joined)
        join the tier
    end if
```




(a) Initial topology (b) Tier construction (c) The resulting topology

**Fig. 3.** Parts of local redundancy links are preserved in the tier structure

TPPSM relies as much as possible on the path-building information already available in the underlying HWMP, thereby limiting the overhead incurred in building tier structure. In particular, it does not employ any special control packets. In fact, extra PREPs and PERRs for tier building and maintenance along with a few extra fields in path-building control packets constitute the only additional overhead in TPPSM relative to HWMP.

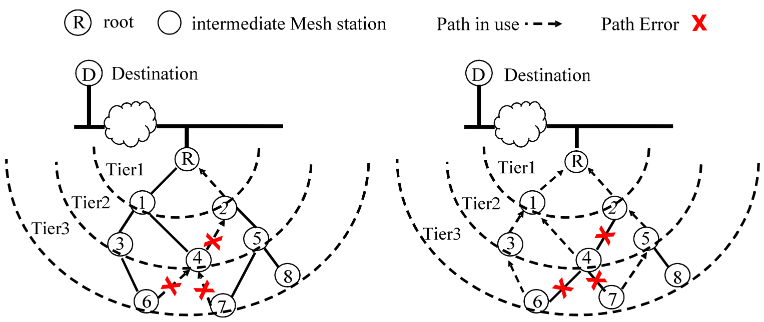
### 3.3 Active Phase

At the end of the tier construction, the tiers are numbered 1, 2, 3, … starting from the innermost tier (root station) and are organized such that a station in the $n^{th}$ tier can relay a message to the root station in $n$ hops. In this way, routing can be done at the level of a tier. If multiple neighbors with a lower tier-rank exist, they can be used for path recovery or to control congestion.

The following are given to describe the operations in detail.

*Path recovery:* As the data transmission occurs, if an active path is no longer usable, the mesh station may distribute residual traffic to an alternative lower tier rank neighbor immediately after detecting the link failure, as shown in **Fig. 4**.

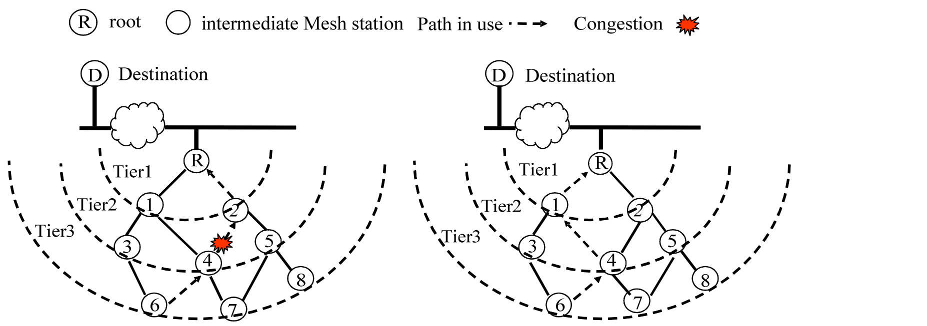
The path maintenance in TPPSM is a simple extension to HWMP path maintenance. Like HWMP, TPPSM also uses PERR packets. A station generates or forwards a PERR when the last path to the destination breaks. TPPSM also uses PREQ with an incremental sequence number to distinguish stale path and fresh path information.




(a) Path error (b) Forwarding data to alternative neighbor with lower tier rank

**Fig. 4.** Path recovery

*Congestion Control:* A mesh station that detects congestion and the incoming traffic source causing this congestion, following the congestion control rules in the draft, transmits a Congestion Control Notification frame to the mesh stations of its traffic source or to other neighboring mesh stations as specified by the active congestion control protocol. We propose that if the queue size of a station is above a maximum threshold, it then sends a Congestion Notification frame to the station that should be controlled. The one with the highest packet injection speed is considered to be the controlled station. The station that received the message may forward data to an alternative neighbor with a lower tier-rank, as shown in **Fig. 5**, or can apply rate control until the congestion duration specified in the message expires. A list of the processes is summarized in Algorithm 3.




(a) Congestion occurs (b) To alleviate congestion by forwarding data to neighbor with lower tier rank

**Fig. 5.** Congestion control

Algorithm 3: Congestion control algorithm

At a congested station:
  **if** (the queue size of a station is above maximum threshold)
    identify the station that should be controlled
    send a Congestion Notification Frame to the station
  **end if**

At a controlled station:
  When a notification message arrives:
  **if** (an alternative neighbor with lower tier rank exists) **then**
    forward data to the alternative tier
  **else**
    apply rate control until the congestion duration
  **end if**

As noted in Algorithm 3, the tier construction may facilitate the congestion control. We have only proposed this congestion control algorithm in this section of this paper. How the congestion control algorithm should be done exactly under the tier construction, and an estimation of how the congestion control will behave, will be pursued in our future work.

### 3.4 Theoretical Analysis

By organizing the network into concentric tiers, TPPSM utilizes the potential mesh resources to provide the redundancy to the network. This can improve the path stability to some extent in theory.

We first define the stability of the path as follow:

The probability $S(t)$ that a source/destination pair provides a stable communication link for a given length of time $t$ is called the stability of the path.

A single-path has a series of one-hop link so that the failure of any one-hop link causes the entire path to fail. Thus, stability of a single path $S_s(t)$ is given by

$$S_s(t) = \prod_{i=1}^{N} S_i(t) \tag{1}$$

,where $S_i(t)$ is the stability of one-hop link $i$, and $N$ is the number of one-hop links. The life time of radio-link is most commonly modeled by an exponential distribution. We therefore assume that every one-hop link $i$ has a failure rate $\lambda_i$. Equation 1 can be expressed as:

$$S_s(t) = e^{-\lambda_s t} = e^{-\Sigma\lambda_i t} \quad (2)$$

,where $\lambda_s = \Sigma\lambda_i$ is the failure rate of the whole path. Thus, the *Mean Time To Failure* of a single-path ($MTTF_s$) is

$$MTTF_s = \int_0^{\infty} t \cdot \lambda_s e^{-\lambda_s t} dt = \frac{1}{\lambda_s} = \frac{1}{\Sigma\lambda_i} \quad (3)$$

A link-disjoint multi-path has a set of parallel paths connected so that all the paths must fail before the source-destination communication fails. Thus, stability of a multi-path $S_m(t)$ is given by

$$S_m(t) = 1 - \prod_{j=1}^{N} [1 - S_{sj}(t)] \quad (4)$$

,where $S_{sj}(t)$ is the stability of a single-path $j$, and $N$ is the number of paths between source and destination. Let $\lambda_{sj}$ represents the failure rate of a single-path $j$, Equation 4 can be expressed as:

$$S_m(t) = 1 - \prod_{j=1}^{N} [1 - e^{-\lambda_{sj} t}] \quad (5)$$

If we assume that life-time of all paths are independent and identically distributed with parameter $\lambda_s$ (While this is not strictly the case, here we are seeking general trends, and therefore this approximation is appropriate), the *Mean Time To Failure* of a multi-path ($MTTF_m$) can be expressed as:

$$MTTF_m = \frac{1}{\lambda_s} + \frac{1}{2\lambda_s} + \ldots + \frac{1}{N\lambda_s} = \sum_{j=1}^{N} \frac{1}{j\lambda_s} \quad (6)$$

Here, we can see that multipath can obviously improve the robustness. TPPSM utilizes the potential mesh resources to provide the redundancy to the network. Thus, a redundancy path, between any two tiers, can improve the path stability to some extent.

## 4. Simulation and Analysis

The ns-2 [20] has been used for the simulative evaluation of the HWMP path selection and its different modes. In order to evaluate the effectiveness of the proposed tier-based proactive path selection mode with the proactive tree mode of HWMP, we performed simulations in the ns-2. Each traffic flow consists of UDP packets with a payload of 512 bytes.

### 4.1 Evaluation Metrics

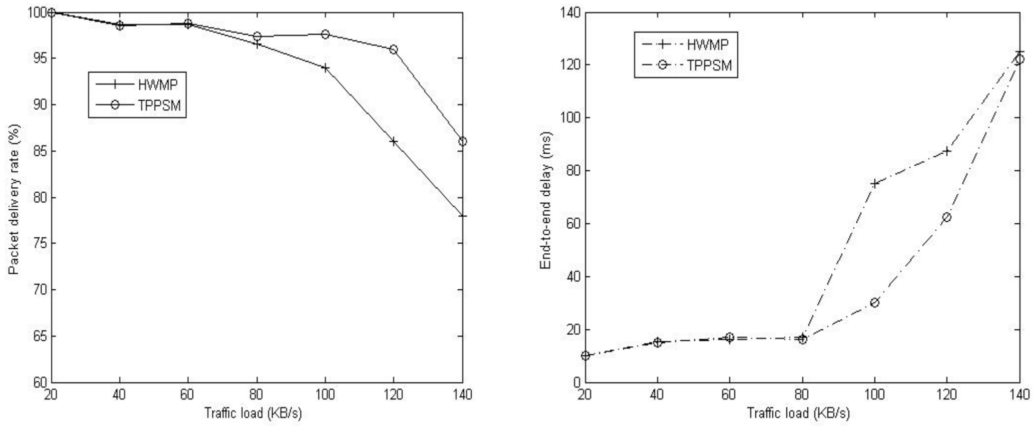
The protocol performance was evaluated in our simulation with the following metrics:

(1)The *packet delivery ratio* is the ratio of data packets that are successfully received by the destination mesh stations to the number of data packets being sent by the source mesh stations.

(2)The *end-to-end delay* represents the average time difference on successfully received data at the destination node from the source node.

### 4.2 Varying Traffic Load

Thirty-five mesh stations are randomly placed in a 1000m x 1000m square area. The traffic flows are sent between randomly chosen sources and destinations, including the root mesh station. We increase the data rate from 20KB/s to 140KB/s. **Fig. 6** shows performance for varying data rates. The performance degrades in both cases with an increasing data rate (offered load). With very low packet rates, the stress of maintaining a path is relatively low. TPPSM is not very effective in such scenarios, because there are not enough stations to take advantage of the alternate tiers. With very high packet rates, the relative performance gain with TPPSM increases.

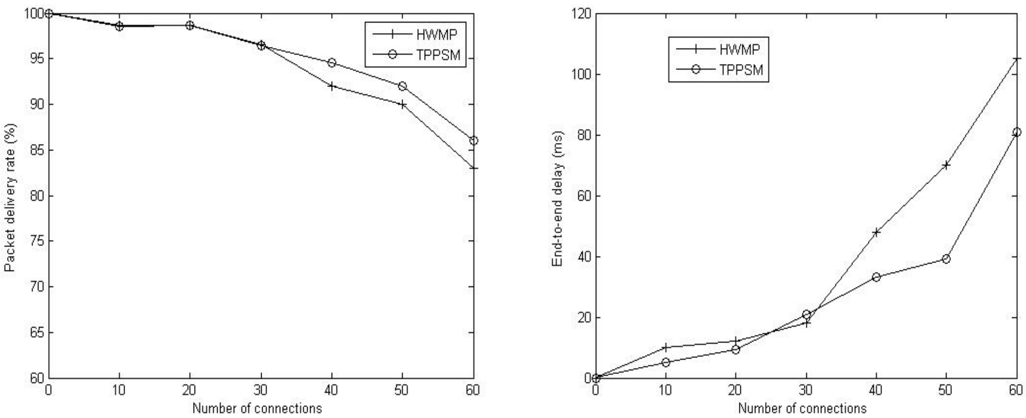



(a) Packet delivery rate (b) End-to-end delay

**Fig. 6.** Performance for varying traffic load

### 4.3 Varying Number of Connections

Increasing the number of connections requires the protocol to maintain more paths between the root and station pairs, thus stressing the traffic to the root station. **Fig. 7** shows various performance metrics as a function of the number of connections. The performance of both protocols degrades with an increasing number of connections. With a smaller number of connections, the difference between HWMP and TPPSM is not noticeable. However, with an increase in the number of connections, TPPSM tends to perform better. This is consistent with the expectation that the TPPSM has a better ability to handle the stress of connections.



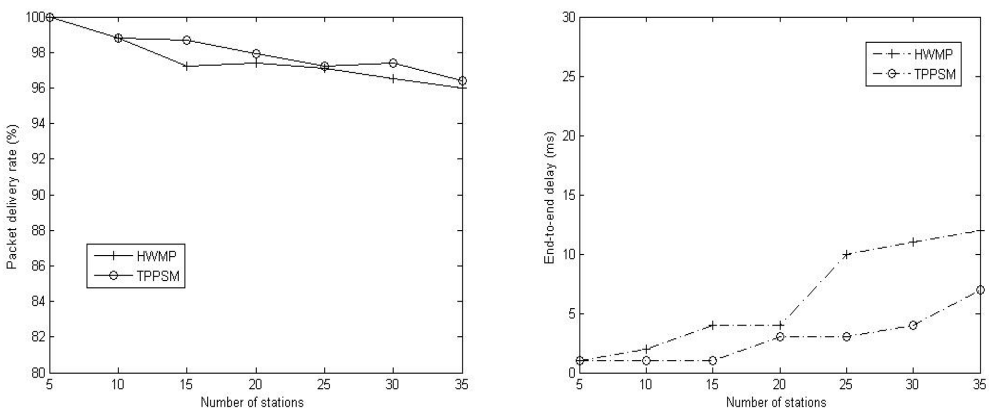

(a) Packet delivery rate (b) End-to-end delay

**Fig. 7.** Performance for varying numbers of connections

### 4.4 Varying Number of Stations

We studied the behavior of our model when the number of stations in the network grows. Different experiments are executed in which the number of associated stations in the network increases from 5 to 35. The time at which each station started its transmission was not synchronized.

Increasing the number of stations will increase the number of tiers. The **Fig. 8** demonstrates the effect of increasing the number of stations on all protocols. When there are only a few stations, the difference for all modes is not very noticeable. However, with an increase in the number of stations, TPPSM tends to perform better. This shows that TPPSM, by virtue of utilizing the potential available mesh links in tiers, is better able to handle the stress of data delivery.




(a) Packet delivery rate (b) End-to-end delay

**Fig. 8.** Performance for varying numbers of stations

## 5. Conclusion

The central stations in the tree topology established by the proactive tree mode in the HWMP are likely to suffer from contention in the bottleneck links when the network has a high traffic load. A failure of the central station (e.g., a crash or simply going into sleep mode to save energy) can cripple the whole network in the tree topology.

In a connected mesh topology, stations with two or more radio links between them are connected so that if a failure occurs in any of the links, the other link provides redundancy to the network.

We proposed a Tier-based Proactive Path Selection Mode in this paper. By organizing the network into concentric tiers, the potential mesh resources can be utilized to provide redundancy to the network, which facilitates path recovery and congestion control so as to improve the end-to-end transmission performance. The simulation results show that the TPPSM has better performance than the proactive tree mode of HWMP.

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**Zhang fuquan** received an M.S. in Computer Science from Shenyang Li Gong University in 2005. From 2006 to the present, he has been a PhD candidate at the Network Computing Laboratory, Hanyang University, Seoul, Korea. His research foci include 3G/4G cellular systems and wireless mesh networks.

**Inwhee Joe** received B.S. and M.S. degrees in Electronics Engineering from Hanyang University, Seoul, Korea, and a Ph.D. in Electrical and Computer Engineering from the Georgia Institute of Technology, Atlanta, GA, USA in 1998. Since 2002, he has been a faculty member in the Division of Computer Science & Engineering at Hanyang University, Seoul, Korea. His current research interests include wireless sensor networks, 3G/4G cellular systems, mobility management, multimedia networking, and performance evaluation.

**Yong-Jin Park** received his B.E., M.E. and D.E. degrees in Electronic Engineering from Waseda University. During 1978 - 2010, he joined Hanyang University, Seoul, as a full-time faculty member. He visited the Department of Computer Science, University of Illinois, Urbana-Champaign, as a Visiting Associate Professor from 1983 to 1984. He also visited Computing Laboratory, University of Kent, Canterbury, England from 1990 to 1991 as a Research Fellow. He was the President of Open Systems Interconnection Association, from 1991 to 1992, Chairman of IEEE Seoul Section from 1999 to 2000, Director of Secretariat of APAN (Asia Pacific Advanced Network) during 1999 – 2003, President of KIISE (Korea Institute of Information Scientists and Engineers) in 2003, and Director of IEEE Region 10 during 2009-2010. He joined Waseda University from April 2010, where he is a professor. Currently he is a Professor Emeritus of Hanyang University. His main research interests are computer networking and mobile/ubiquitous computing