

System Study of the Wireless Multimedia Ad-hoc Network based on IEEE 802.11g

Chung-Wei Lee

Department of CS, University of Illinois, Springfield, IL, USA

Jonathan C.L. Liu and Kun Chen

CISE Department, University of Florida, Gainesville, FL, USA

Yu-Chee Tseng and S.P. Kuo

College of Computer Science, National Chiao-Tung University, Hsin-Chu, Taiwan

Abstract

The construction of a wireless multimedia ad-hoc network needs to go across the mixed environment with the indoor, the wall-penetration, and the outdoor condition. This paper presents our contribution to address the system design aspects of a multimedia-enabled network based on IEEE 802.11g ad-hoc mode. There are distinct differences between indoor and outdoor environment and penetrating the walls stressed the system limit of the 802.11g ad-hoc mode. Therefore, routing decisions should be made intelligently with the environmental respect to maximize the bandwidth support on the end-to-end paths.

By investigating the experimental results of the average throughput with the 802.11g ad-hoc mode, we have collected the different performance characteristics among the indoor, the wall-penetration and the outdoor environment. Via the experiments and analyses, we have observed that the ad-hoc mode had the worst performance within 5 meters in indoor environments. In outdoor environments, TCP seemed to favor either short distance (e.g., 5 meters) or long distance (e.g., 25 meters). On the other hand, the best performance UDP has achieved with the distance of 10 meters. When the wall-penetration occurs, it is important that the routing nodes in the building edge areas are placed close-by within 5 meters.

Given the solid evidences from the baseline experiments, we have embedded the heuristic algorithms into the routing decisions. We have thus simulated a large area of 300 meters by 300 meters with hundreds of routing nodes. After investigating over 100 (randomly-generated) topology scenarios, the performance results indicate that our proposed scheme produces the higher-bandwidth paths for most of the cases. Even in the less-dense cases, our proposed schemes still can find the better paths with bandwidth about 30% higher than the conventional methods.

1. Introduction

Many places (especially rural areas or military battlefields) are lack of the support of access points or base stations. Thus, a wireless multimedia network will not be complete without the support of the ad-hoc mode. Ad-hoc networks do not go through the conventional network infrastructures like access points/base stations or routers. Thus the routing functions need to be provided by the peer nodes in the middle of the paths. Building an ad-hoc network imposes more difficulty since the communication relies solely on the ad-hoc mode (instead of infrastructure mode).

As the authors in [FKFB05] pointed out, video communication requires the support of high-bandwidth guarantee from the 802.11 wireless networks. Thus, 54-Mbps 802.11g should be explored to replace the 11-Mbps 802.11b networks. However, the 54-Mbps 802.11g networks impose much higher restriction on the distance covered. Therefore, achieving the high-bandwidth guarantee requires the careful planning on the node locations (as we will demonstrate later).

In addition, since a truly ad-hoc network will possibly go across the mixed environments from indoor, walls to outdoor condition, it is important to obtain the baseline performance with different conditions. There are distinct differences between indoor and outdoor environments for the 54-Mbps 802.11g networks. Indoor environment always impose with ceiling and walls, which allow the signal to have more ways to propagate the signals. It is also true that indoor environments may also impose many objects (e.g., desks and chairs) which intend to scatter the signals.

On the other hand, outdoor environments do not impose ceiling, thus the signals tend to propagate like water ripples. But the natural obstacles as well as temperature and humidity condition may also play a role on the effective bandwidth that the system can achieve. The moving objects such like cars and people are also the factors affecting the results.

Consider Fig. 1 as a simplified example: The source nodes in Building 1 can't directly talk to the destination nodes in Building 2 due to long distance. Thus the connection needs to be built via the routing nodes in between. Some of these routing nodes are within the Building 1, some of them are located outdoors. Since the ad-hoc mode of 54-Mbps 802.11g network interface cards only reach no more than 30 meters, some routing needs to be performed within the indoor environments.

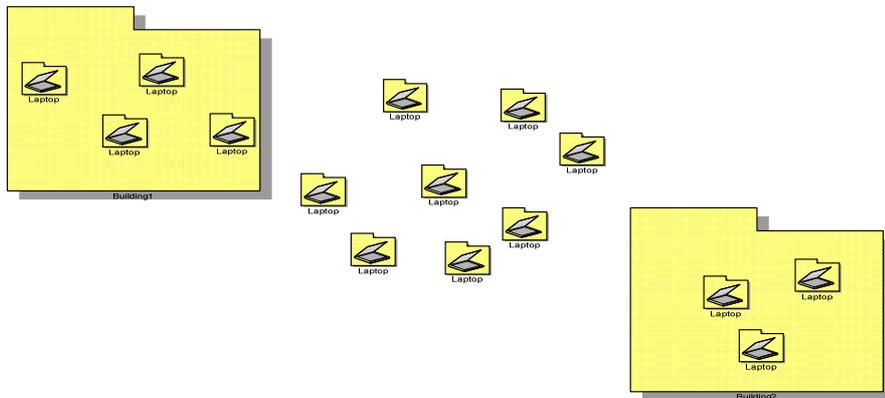


Figure.1 An Example of the ad-hoc 802.11g network (every laptop is served as a node)

After the connection setup reaches to the edge of the building, the signals need to penetrate the building walls to reach the routing nodes outside the building. Then the connection will be maintained by the routing nodes in the outdoor environments. Eventually the connection reaches to the edge area of the Building 2, which needs another signal penetration to reach the nodes inside the indoor environment again.

Ideally, the paths can be constructed automatically by locating the proper routing nodes such that the overall bandwidth can be maximized. Nevertheless, it is not clear how 802.11g ad-hoc mode performs under these different environments and how much the distance factor will contribute the overall performance. The environmental effects should be taken into consideration when it comes to distributed multimedia applications which require high-bandwidth support. Therefore, the routing algorithms should be also adaptive with respect to the different environments. In order to construct a truly ad-hoc network, we thus firstly investigate the average throughput between two laptop computers with the ad-hoc mode. Most importantly, it is our hope that different performance characteristics between indoor and outdoor settings can be collected. Then, these characteristics will be used by us to model a large-scale wireless ad-hoc network.

Since wireless environment (including ad-hoc networks) does introduce much higher error rates for the data transmission, users hardly enjoy the peak performance reported by the *netperf* tools. Instead, the average performance is perhaps the true one experienced by the common users. We thus developed the software tools that benchmark the average performance achieved by the ad-hoc communication. Our benchmarking software emulates the constant streaming of multimedia data between two hosts. One host decides the sizes of messages in block of video/audio frames, and transmits the messages to the other host. Once the other host receives the messages, it will prepare the identical sizes of messages for sending back to the sending host. This process is similar to the video/audio conferencing scenarios between two hosts, and has been accepted by the research community [GPLRS95, LDHL96, LDSHL99, DLS01, WEL02, WLC03, LCL05, KL05, KL06].

Conventional thought usually predicts that the achieved bandwidth of the ad-hoc networks should be higher when the distance between the two laptop computers is short. However, the preliminary results indicate that this common myth is not always true. Via the experiments and analysis, we have observed that the ad-hoc mode had the worst performance within 5 meters in indoor environments. We also observed that UDP can outperform TCP up to 38.5% in achieved (average) bandwidth.

In outdoor environments, TCP and UDP have demonstrated different performance behaviors. TCP seemed to favor either short distance (e.g., 5 meters) or long distance (e.g., 25 meters). On the other hand, the best performance UDP has achieved with the distance of 10 meters. Apparently, the connection setup in outdoor environments should be also determined by the types of protocol stacks.

Penetrating the walls stressed the ad-hoc mode to the limit. The performance results indicate that the distance between the routing nodes should be placed with 5 meters away. Therefore, it is important that the routing nodes in the building edge areas are placed close-by within 5 meters (across the wall). Otherwise the overall bandwidth for the connection will be significantly affected by the wall-penetration.

These unique observations indicate that the construction of an ad-hoc wireless network needs to place the distance factor in serious consideration. Apparently, the network interface cards do not necessarily work well when the devices are close-by. A proper distance range should be maintained all the time between the routing nodes.

For many network applications such as video streaming, sufficient path bandwidth is critical to their end-to-end performance. Given the solid evidences from the baseline experiments, the routing decisions within the (multi-hop) ad-hoc networks need to be intelligent enough to guarantee the sufficient bandwidth. We have thus proposed the *MaxThroughput* algorithm to find the paths with sufficient bandwidth guarantee. The effectiveness of the algorithm is then proved over a large area of 300 meters by 300 meters with hundreds of routing nodes.

The preliminary results indicate that, even the node number is small and path selection is limited, our proposed schemes still can find the better paths with bandwidth about 30% higher than the conventional methods. With the higher density, the bandwidth of the selected paths can be 3.8 times higher compared to the conventional schemes. After investigating over 100 (randomly-generated) topology scenarios, the evidences indicate that our proposed schemes produce the higher-bandwidth paths for most of the cases.

The rest of the paper is organized as the following: Section 2 introduces the related study. Section 3 and 4 provide the unique finding and analysis of the baseline performance related to the distance factor. The proposed *MaxThroughput* algorithm is described in details in Section 5 along with the performance results in Section 6. Finally Section 7 concludes the paper with our remarks.

2. Background and Related work

In general, finding the optimal routing solution to satisfying multiple quality of service (QOS) factors within the networks is a NP-complete problem [LLCN01] [LCL05] [ZLGKMT05]. Therefore, heuristic methods are usually thought to speed-up the searching for the good-enough solutions in the large-scale networks. The wireless ad-hoc networks make the routing problem even more complex. In addition to the conventional QOS factors, the physical distances between the routing nodes with the environment factors should be jointly considered. [GJTW05] also recognized that the conventional QOS routing schemes might not fit the wireless ad-hoc networks at all. They also suggested that heuristic algorithms should be explored. However, for their investigation, only the interference within the physical layer was considered. Our investigation considered the joint effect above the network layers.

There is little literature actually addressed the concerns that we have on the distance factor, but some of the previous studies can be considered loosely related. [KH04] analyzed the detailed operations of 802.11 and proposed models to reduce the idle-time while under the collision. The work seemed to apply to the infrastructure mode instead of ad-hoc mode. Distance factor in addition to wall effect was not considered. [SWL04] focused on the load-balancing methods to reduce the control message overheads. The distributed- and hop-based AODV (Ad-hoc On-demand Distance Vector) algorithm [PRD02] was assumed in their study. Just recently, [SPH04] and [HHL06] also proposed to use hybrid methods and probability (i.e., gossip) to reduce the control message overhead due to the flooding inherited in AODV, DSR, ZRP and TORA. Our work is focused on the data communication plane. The control and data planes are processed separately by routing nodes. Nevertheless, their work can be jointly considered with our work to handle the control messages efficiently.

[FML03] addressed the re-design of TCP to provide fairness between UDP and TCP streams. The work is based on 11-Mbps 802.11b with simulation work only without considering the distance factor or wall effect. Our work is focused on 54-Mbps 802.11g with actual experiments and our proposed schemes improve the performance of both UDP and TCP. [XL04] [HD04] also recognized that original 802.11 DCF had a focus on the infrastructure mode instead of the ad-hoc mode. Their work was focused on the admission control schemes, which is beyond the scope of this paper.

3. Baseline Experiments

Laptop computers are adopted to perform the actual experiments. Both of them have Pentium IV processor (with Centrino Technology), 512M memory and 40G hard disk. We

then used two identical wireless adapters to be installed within the laptop to carry out this experiment. The Linksys 802.11g wireless cards use 2.4-GHz frequency with the theoretical bandwidth up to 54Mbps. The mode has been set in ad-hoc mode and the number of channel is set to six. The subnet mask is set as 255.255.255.0 with gateway function disabled.

In addition to the identical hardware, we also adopted the same operation system (Microsoft Windows XP) on the laptops. This typical OS/hardware configuration perhaps represents the popular platform for over 90% of end users. We then built our own benchmarking software on top of the TCP/UDP/IP protocol stack embedded in Windows XP operating system.

Our benchmarking process can be repeated with a predefined number of times (e.g., 100 times in our experiments) to provide the useful statistics based on the round-trip delay time measurement. In addition, our benchmarking software discards the top 2.5% and bottom 2.5% of the measured results. Thus, our results represent the 95% interval of the average performance. Therefore, instead of reporting the best or worst results, our reported data actually reflect what the typical performance will be. We believe this approach of measurement will be more trustworthy for the common users.

In order to get a complete view of the throughput result, we used both TCP and UDP to test the throughput. And we also did the experiments in three different environments: indoor without obstructions, outdoor without obstructions, and one laptop indoor with the other outdoor but one wall in-between them, we call this situation as the wall-penetration situation.

3.1 Indoor without obstructions

For this experiment, we chose the Computer Information Science Engineering building basement as our experiment location in order to minimize the interference of access point of the infrastructure wireless connections. In the basement, we chose a straight hallway about 30 meters long, and then put one laptop at each side. The experiment environment is as Figure 3. And then we did the experiment at three distances: TCP, UDP with distance within 5m; TCP, UDP with distance at between 5m and 10m; TCP, UDP with distance between 10m and 20m.

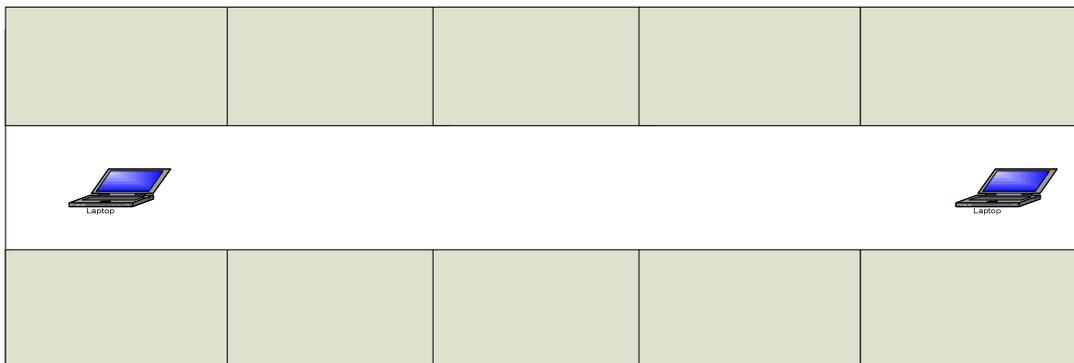


Figure 3. Indoor Experiment Environment

3.2 Outdoor without obstructions

For this experiment, we chose a large parking lot at VA hospital, and did the experiments when there are few cars far away parked in order to minimize the interference of cars. And also, as we did in the indoor without obstructions experiment, we did the experiment at 5m, 10m, 15m 20m and 25m.

3.3 Penetrating wall

For this experiment, we put one laptop indoor, and the other laptop outdoor, then we fixed the indoor laptop's position, moved the outdoor laptop so that the distance between them is changing with distance: 5m, 10m, 15m, and 20m. In between them there is a wall as the obstruction, the wireless signal has to penetrate the wall. In order to minimize the interference of the AP wireless connection, we chose New Physics Building basement as the experiment environment. The experiment environment is as in Figure 4:

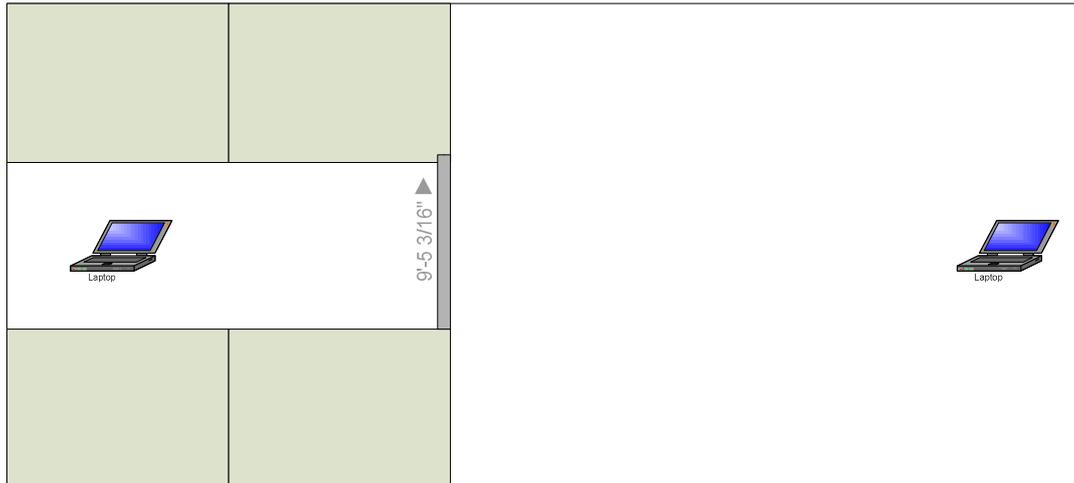


Fig 4. Penetrating Experiment Environment

4. Experimental Results and Analysis

4.1 Indoor without Obstructions

Fig 5 depicts the results of TCP experiment performed in the indoor environment. The achieved throughput performance is indeed affected by the size of messages communicated with the two hosts. With the increasing message sizes, the throughput has been improved accordingly. For instances, with the message size of 32-Kbyte (i.e., 2^5 -Kbytes in Fig 5), TCP only achieves in the range of 11 Mbps (i.e., 19% of the theoretical 54-Mbps peak bandwidth).

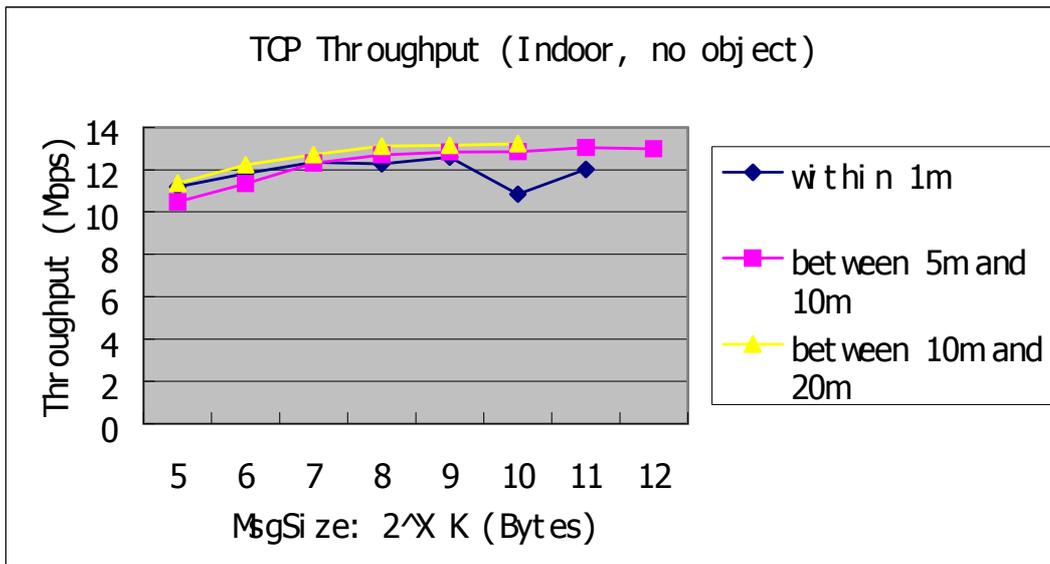


Figure 5. Indoor TCP throughput

With the message size of 4-Mbyte (i.e., 2^{12} -Kbytes in Fig 5), the throughput can be achieved to 13 Mbps. The 2-Mbps performance improvement represents the 18% increase from 32-Kbyte message size. Just like the wire-line networks, larger messages cause smaller software overhead. Thus, the results are considered reasonable.

However, an interesting observation has been found related to the distance factor. Unlike the wire-line networks, the communication pair in ad-hoc networks can move their position more freely. It is the conventional thinking that the throughput performance should be better when the distance is shorter. The reason behind the expectation is that the time to propagate the messages to the destination is shorter. Interestingly, our measured performance results indicate the opposite trend. We expected the performance should be best with the distance less than 5 meters away. But it turns out the ad-hoc mode performs the worst compared to the distance [5m, 10m] and [10m, 20m]. The observed performance trend demonstrates that increasing the distance does improve the achieved throughput performance.

There are perhaps a number of reasons for causing this unique performance trend. One of the reasons can be related to the multi-path propagation of the radio frequency in the physical layer. When the distance is less than 5 meters, the transmitted signal for LOS (line of sight) transmission is affected by the other reflection, diffraction and scattering radio frequencies [K85]. Though the LOS signal arrives quickly, the signal timing and strength from the multi-path signals can be quite different. Therefore in the MAC Layer, the delay differences can be great enough that bit errors occur. Thus, the receiver can not distinguish the symbols and interpret the corresponding bits correctly. When the distance is increased, the multi-path interference is reduced because the timing and strength difference between LOS and non-LOS signals can be insignificant.

This unique performance trend is also demonstrated via the UDP protocol stack. The following Fig. 6 depicts the results for unit size variance between UDP and TCP. We can observe that with the increase of unit size, the throughput for UDP is increased correspondingly.

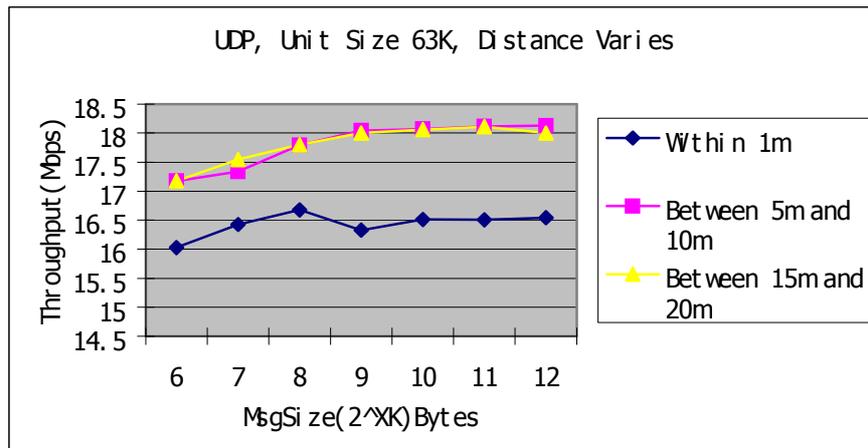


Figure 6. Unit Size influence

Without the complex congestion control as TCP does, UDP protocol stack further reduces the overhead for the different message sizes. For the same amount of data, the segmentation will be also less than the small unit size situation. Due to the deduction of the headers and overheads, the throughput performance increases significantly. The peak average throughput does reach 18 Mbps, which is 5 Mbps (i.e., a further improvement of 38.5% from TCP).

The UDP protocol stack almost reaches to the 18.2 Mbps when the message size is about 2 Mbyte (i.e., 2¹¹ KByte in Figure 7). The similar performance trend is still observed, with the much-less bandwidth achieved when the distance is less than 1 meter. However, unlike TCP protocol stack, the achieved bandwidth seems to be quite identical when the distance is greater than 5 meters away. This unique observation makes us believe that the ad-hoc network nodes should be placed at least 5 meters away, when supporting the UDP-based distributed multimedia applications.

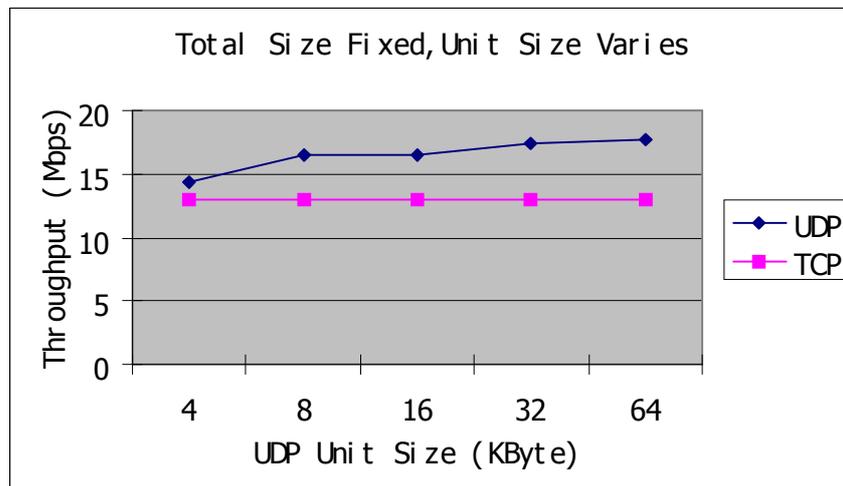


Figure. 7 Indoor UDP throughput

4.2 Outdoor without Obstructions

As we explained in the *Introduction* section, outdoor environments can be complex due to the road condition with cars and walking people. In addition, natural and artificial objects are also co-existed in the environment. In this paper, we eliminate some factors since we performed the experiments in the university campus. Thus, there were no fast-moving objects except the jogging or bike-crossing by students. Natural objects (e.g., trees) and artificial ones like trash cans also exist, but we try to avoid them as much as possible.

The TCP protocol stack's throughput performance results for outdoor environment are shown in the following Fig.8. We can observe that although the throughput results still vary due to the distance variation, the trend does not indicate the similar behavior as indoor ones with the short distance. We believe the multi-path interference has a small effect in the outdoor environments for the TCP-based application.

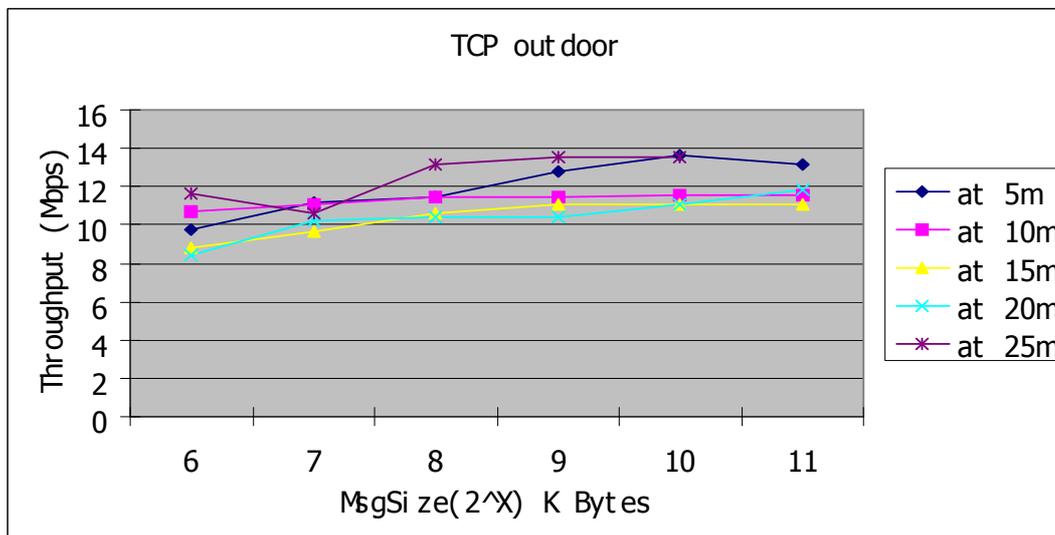


Figure 8. Outdoor TCP Throughput

Thus, unlike indoor environments, TCP protocol stack seems to perform the best when the distance is either 5 meter or 25 meters away in the outdoor environment. The TCP protocol stack seems to perform the worst when the distance is 20 meters away. We are still in the process to verify the reason(s) to explain why this major difference occurred. Nevertheless, the current observation call for the ad-hoc network nodes to be placed either 5 meters or 25 meters apart when they are located in the outdoor environment.

The following Fig.9 depicts the UDP protocol stack's experimental results. The performance was further improved to reach 19.1 Mbps when the message size is large (e.g., 2 MByte). The best performance results were demonstrated with the distance was 10 meters. However, when the message sizes exceed 256 Kbytes (i.e., 2^8 Kbytes), the distance factors have limited impact on the achieved bandwidth.

The overall observations thus support more placement flexibility when designing the ad-hoc networks, especially when the messages sizes are larger than 256 Kbytes. To support high-quality video streams, we also advocate for large-message sizes for the performance-guarantee among concurrent accesses.

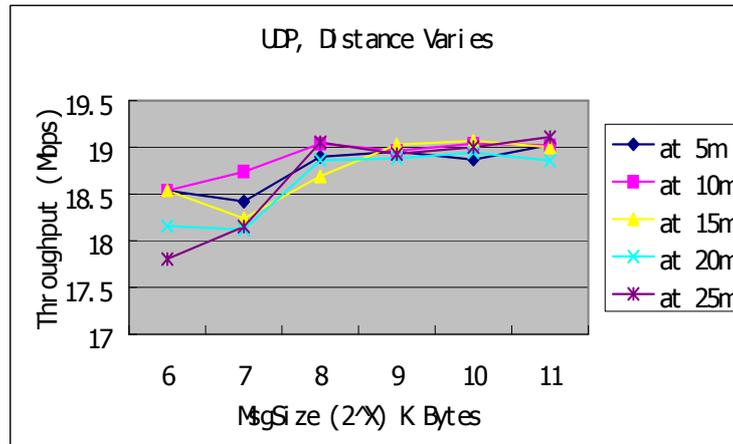


Figure 9. Output UDP Throughput

4.3 Penetrating wall

It is expected that the ad-hoc wireless networks to support the users no matter where they are. Therefore, it is common that the links between the routing nodes need to penetrate the walls between them. The penetration process needs to happen when the links are constructed between the indoor and outdoor environments.

Modern buildings seem to be constructed with bricks and concrete. The radio signals generated from the wireless network interfaces need to penetrate the walls. After the penetration, the signals need to be strong enough for the routing nodes to detect them. Fig.10 depicts the achieved throughput for TCP penetrating the walls.

We can observe from Fig.10 that when the RF penetrates a wall, throughput performance is dramatically dropped. We can observe that when the distance between the nodes is increased, the achieved throughput will be decreased. It proves that the signal strength is reduced significantly after penetrating the wall. The distance factor becomes very critical in this situation.

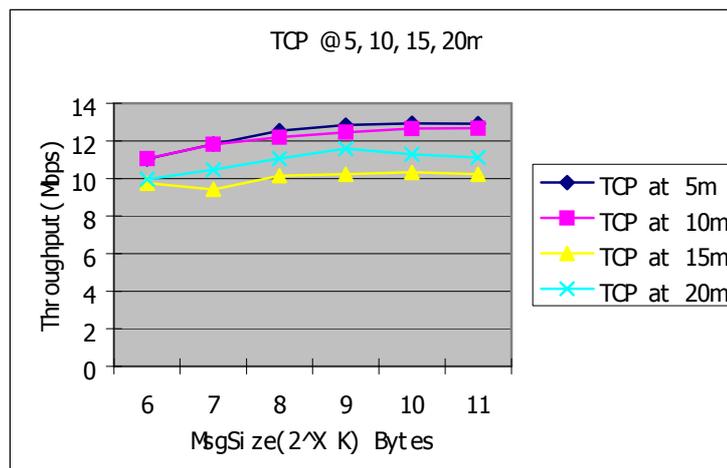


Figure10. TCP Penetrating Wall Results

For instance, the experimental results demonstrate that perhaps the proper distance between any two nodes should be around 5 or 10 meters. Larger-than-10 meters will cause the network bandwidth to be reduced significantly (e.g., 25% loss from 12 Mbps to 9 Mbps when the distance is 15 meters). We believe this observation is unique and important when an ad-hoc wireless network is constructed.

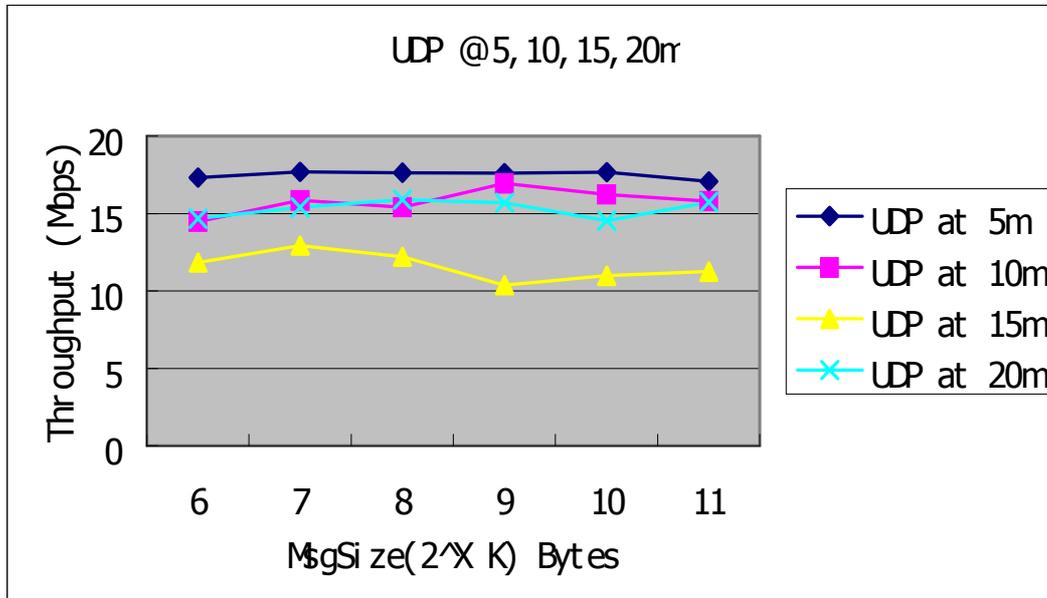


Figure 11. UDP Penetrating Wall Results

The UDP performance behavior follows the similar pattern. The worst-case performance reduction occurred with 15 meters and 512 Kbyte (i.e., 2^9) message size. The performance reduction is almost 44% (i.e., from 18 Mbps to 10 Mbps).

5. Proposed Schemes and Protocols

The discovery of IEEE 802.11g's throughput-distance relationships in its ad-hoc networking mode has significant impact in QOS routing. Since the bandwidth allocation is the top priority of the routing decision, the baseline performance results indicate that proper paths should be chosen with the consideration of the distance between any two routing nodes. However, the majority of the existing schemes seem to be lack of the joint consideration with the distance factor. For instances, many assumed the bandwidth is uniformly identical within the distance limit, thus the routing decisions favor the minimal number of hop counts. We believe, given the solid evidences from the baseline experiments, the routing decisions within the (multi-hop) ad-hoc networks should be different.

In our simulations, each network topology is generated by the following *RandomTopology* algorithm. It first places n (ranges from 10 to 200) nodes randomly in a grid. Then if there are isolated nodes (i.e., nodes are not within any other node's transmission range), they will be removed because their existence does not contribute to the routing process. If this occurs, more nodes will be created at random locations until there are n connected nodes in the topology. When this is done, all links will be assigned a link bandwidth according to our findings in 802.11g's throughput-distance relationship based on

their relative distance. The distance can be obtained from GPS position and calculation as in [TCC06].

With each topology, our *MinHop* and *MaxThroughput* routing strategies are put into test. They are implemented based on *Dijkstra's* link state algorithm [KR04] with proper modifications. The *MinHop* algorithm computes minimum-hop paths from the source node u to all other nodes in the topology, and returns the path bandwidth for all paths. On the other hand, the *MaxThroughput* algorithm searches routes with maximum end-to-end path bandwidth between any pair of nodes, and return the results.

The pseudocode and notation for *RandomTopology*, *MinHop*, and *MaxThroughput* are presented as follows:

Notation:

- $bw(i,j)$: link bandwidth as a function of physical distance
- $H(v)$: current hop count from the source node u to destination v
- $B(v)$: current path bandwidth from the source node u to destination v
- N : the set contains all nodes in a topology
- N' : a subset of N

Algorithm RandomTopology(n)

Randomly place n nodes in a 300×300 area
Calculate link distance between any two nodes
Remove isolated nodes
Repeat above until there are n connected nodes
Assign $bw(i,j)$ to all links

Algorithm MinHop(u)

Initialization:

```
N' = {u}
for all nodes v
  if v is a neighbor of u
    then H(v) = 1
  else H(v) = ∞
```

Loop

```
find w not in N' such that H(w) is a minimum
add w to N'
update H(v) for each neighbor v of w and not in N':
H(v) = min( H(v), H(w) + 1 )
```

until $N' = N$

Calculate path bandwidth $B(u,v)$ where $v \in N$ and $v \neq u$:

$B(u,v) = \min(\text{link_bandwidth for all links on this path})$

Return all $B(u,v)$

Algorithm MaxThroughput(u)

Initialization:

```
N' = {u}
for all nodes v
  if v is a neighbor of u
```

```

    then B(v) = bw(u, v)
    else B(v) = 0
    
```

Loop

```

    find w not in N' such that B(w) is a maximum
    add w to N'
    update B(v) for each neighbor v of w and not in N':
        B(v) = max( B(v), min( B(w), bw(w, v) ) )
    until N' = N
    
```

Return all B(u,v) where $v \in N$ and $v \neq u$

6. Large-Scale Simulations

We conducted a series of QoS routing simulation experiments in order to quantitatively compare two different routing strategies. The experiments were designed to handle the large-scale cases. For instance, we believe an area of 300 meters by 300 meters with hundreds of routing nodes should be considered. Instead of comparing every existing scheme, we generalize their main concept to be the minimum-hop (*MinHop*) routing that searches paths with minimum number of hop count from end to end. For examples, popular mobile ad-hoc QoS routing protocols based on DSR or AODV have the similar concept since they use paths with the shortest response time.

Our proposed strategy is the maximum-throughput (*MaxThroughput*) routing based on our findings in 802.11g's throughput-distance relationship. It finds routes that provide the highest end-to-end path throughput (bandwidth) by jointly considering the distance factor. To model the wireless link bandwidth in the simulations, a piecewise linear function as shown in Fig. 12 is defined based on the baseline performance set with UDP. Since we target the multimedia communication as the long-term application goals, UDP seems to be the right choice (with application-level error correction).

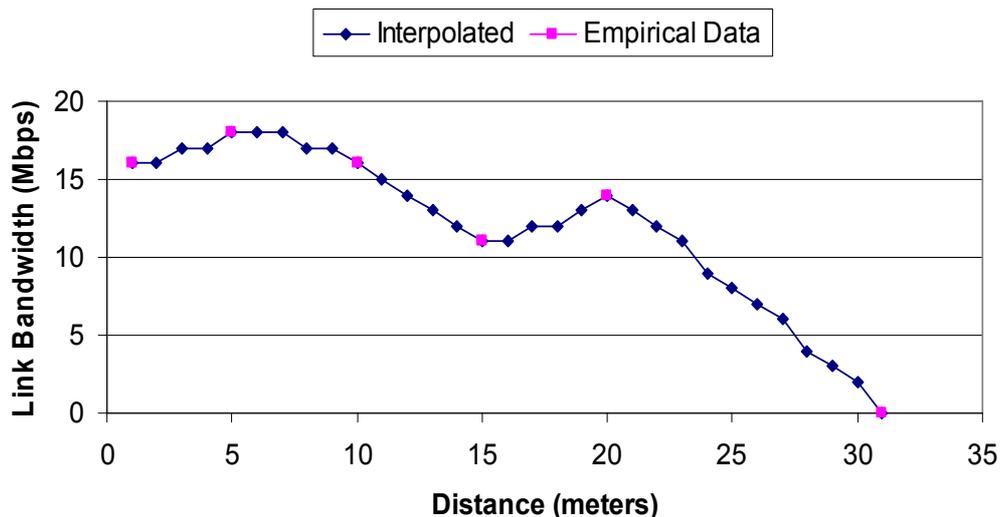


Figure 12. Ad-hoc link bandwidth assignment as a function of physical distance.

This set of data represents the typical wireless ad-hoc networking scenarios which need to come across indoor and outdoor environments. For instances, disaster recovery in collapsed buildings or battlefields with obstacles usually need to support the communication via a mixed indoor/outdoor environment. Interpolation is used to obtain bandwidth values between two adjacent distance points of the empirical data.

In the simulations, the area of 300 meters by 300 meters is specified as the boundary. Then various numbers of nodes (ranging from 10 to 200) are randomly (in terms of location) placed in this area. Having more nodes in a fixed-size area represents higher node density in a wireless ad hoc network. When all nodes are placed in the area, the link bandwidth is determined for every pair of nodes if they are within each other's transmission range. Distance calculation can be performed as the methods in [TCC06]. Then, the two routing strategies, *MinHop* and *MaxThroughput*, are used to obtain path (end-to-end) bandwidth B_{ij} for all possible node pairs (e.g., from node i to node j).

Again, we believe average-case performance results better reflect the reality. Thus, for each node number/density (n), 100 different (random) network topologies are simulated. Our final measurement is the **average** path bandwidth (B_{avg}) over all paths ($n(n-1)/2$) and 100 topologies. That is,

$$B_{avg} = \frac{1}{50n(n-1)} \sum B_{ij}$$

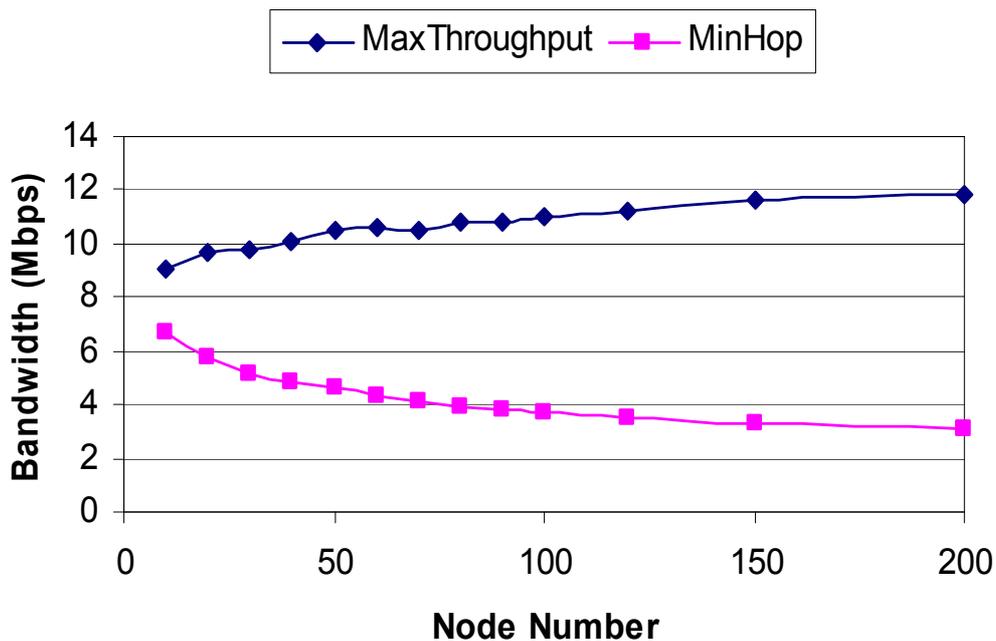


Figure 13. Average path bandwidth as a function of node number in the network.

Fig. 13 shows the average path bandwidth (B_{avg}) as a function of node number/density (n) for *MinHop* and *MaxThroughput* routing. Even the node number is small (low density) and path selection is limited, *MaxThroughput* still can find paths with bandwidth about 30% higher than *MinHop*. As node number increases (higher density with more possible paths), *MinHop* tends to adopt the routing nodes that are far away from each other because this

creates paths with minimum hops. However, the average bandwidth along the path is significantly reduced. On the other hand, with more selections, *MaxThroughput* can reach an average path bandwidth of 11.8 Mbps when node number is 200. At the same time, *MinHop* has only 3.1 Mbps.

Using the simulation framework, we collect the overall results from 100 different topologies. The individual path bandwidth spans from the minimum 1 Mbps to the maximum 18 Mbps. In addition, most importantly, the distribution of all possible path bandwidth values is shown in the following Fig. 14.

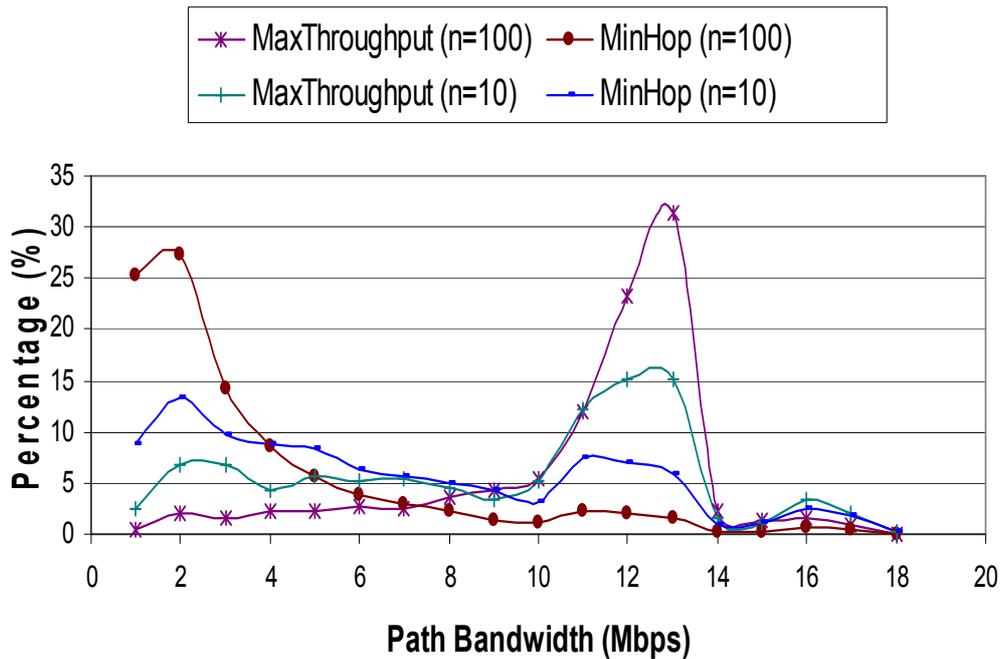


Figure 14. Distribution of path bandwidth

Fig. 14 actually reflects the core differences from the routing heuristics. It provides the insight into the relationships among routing strategy, node density, and path bandwidth. For instances, both routing strategies show flatter distribution curves at the low density ($n=10$) because smaller n implies lacks of path choices. Nevertheless, our proposed *MaxThroughput* scheme still produces more paths (e.g., 17% vs. 8%) for higher average bandwidth (e.g., 12 Mbps).

In high-density networks, the average path bandwidth is strongly affected by the nature of heuristic algorithms. The *MaxThroughput* scheme achieves the highest peak at 31.5% with 13 Mbps paths. The evidences indicate that our proposed algorithm favor the higher-bandwidth paths for most of the cases. On the other hand, conventional schemes prefer short number of hops with the peak distribution of 27.3% with only 2 Mbps paths via the *MinHop* routing strategy. The evidences clearly indicate that, by choosing the shorter number of hops, the distance factor cause the end-to-end path bandwidth loss with a significant degree.

7. Conclusion

There are distinctly performance differences between indoor/outdoor environments and penetrating the walls using the ad-hoc mode. We have performed the systematic experiments to collect the performance characteristics. With the unique findings, our proposed routing schemes have improved the end-to-end bandwidth significantly. Our proposed schemes carefully choose the node-to-node routing distances (e.g., 7 meters and 20 meters in our 802.11g model), therefore improves the quality of user-level applications by providing sufficient bandwidth across the selected paths.

We are in the process to further optimize the performance improvement to suggest that some routing nodes can move away from their current locations (to increase/decrease the distance with some other nodes). With the placement flexibility in the outdoor environment, the system designer can relocate the selected ad-hoc networking nodes into the proper locations. However, achieving the goal of some paths perhaps will affect other paths in the network. Thus, the challenge remains to support concurrent connections simultaneously by achieving the global optimization (between bandwidth, fairness and other QOS factors).

References:

- [DLS01] B. Daines, J. Liu and K. Sivalingam, "Supporting Multimedia Communication over A Gigabit Ethernet Network", *International Journal of Parallel and Distributed Systems and Networks*, Vol. 4, No. 2, Jun. 2001.
- [FKFB05] W. Feng, E. Kaiser, W. Feng, M. Baillif, "Panoptes: Scalable Low-power Video Sensor Networking Technologies", *ACM Transactions on Multimedia Computing, Communications and Applications*, Vol. 1, No. 2, May 2005.
- [FML03] Z. Fu, X. Meng and S. Lu, "A Transport Protocol for Supporting Multimedia Streaming in Mobile Ad-Hoc Networks", *IEEE Journal of Selected Areas in Communications*, Vol. 21, No. 10, Dec. 2003.
- [GPLRS95] A. Guha, A. Pavan, J. Liu, A. Rastogi and T. Steeves, "Supporting Real-time and Multimedia Applications on the MERCURI Testbed", *IEEE Journal of Selected Areas in Communications*, Vol. 13, No. 4, May 1995.
- [GJTW05] R. Gupta, Z. Jia, T. Tung and J. Walrand, "Interference-aware QoS Routing (IQRouting) for Ad-Hoc Networks", *Proceedings of IEEE International Conference on Global Telecommunication (GLOBECOM)*, 2005.
- [HHL06] Z. Haas, J. Halpern and L. Li, "Gossip-Based Ad-Hoc Routing", *IEEE/ACM Transactions on Networking*, Vol. 14, No. 3, Jun. 2006.
- [HD04] J. Hui and M. Devetsikiotis, "Performance Analysis of IEEE 802.11e EDCA by a Unified Model", *Proceedings of IEEE International Conference on Global Telecommunication (GLOBECOM)*, 2004.
- [K85] H. Killen, "Modern Electronic Communication Techniques", Macmillan Publishing Company, New York, 1985.
- [KH04] H. Kim and J. Hou, "Improving Protocol Capacity for UDP/TCP Traffic with Model-based Frame Scheduling in IEEE 802.11-Operated WLANs", *IEEE Journal of Selected Areas in Communications*, Vol. 22, No. 10, Dec. 2004.
- [KL05] E. Kim and J. Liu, "A Integrated Network/Storage Architecture for Sharing High-Quality Broadcast Video", *IEEE Communication, Special Series in Consumer Communication and Networking*, Vol. 43, No. 9, Sep. 2005.
- [KL06] E. Kim and J. Liu, "Design of HD-Quality Streaming Networks for Real-time Content Distribution", *IEEE Transactions on Consumer Electronics*, Vol. 52, No. 2, May, 2006.

- [**KR04**] J. Kurose and K. Ross, *Computer Networking: A Top-Down Approach Featuring the Internet* (3rd edition), Addison Wesley, 3rd edition, 2004, ISBN: 0321227352.
- [**LCL05**] C. Lee, R. Chow and J. Liu, "Enhancing Aggregate QoS for Video Streaming", *International Journal on Computer Communications*, Vol. 28, No. 18, Nov. 2005.
- [**LLCN01**] C. Lee, J. Liu, R. Chow and R. Newman, "Altruistic QoS Routing with Multimedia Dispersion", *Proceedings of International Conference on Multimedia and Exposition 2001 (ICME 2001)*, Tokyo, Japan, pp. 609--612, Aug. 2001.
- [**LDHL96**] J. Liu, D. Du, J. Hsieh and M. Lin, "Performance of a Storage System for Supporting Different Video Types and Qualities", *IEEE Journal of Selected Areas in Communications*, Sep., 1996.
- [**LDSHL99**] J. Liu, D. Du, S. Shim, J. Hsieh and M. Lin, "Design and Evaluation of A Generic Software Architecture for On-Demand Servers", *Special Issue on Multimedia*, *IEEE Trans. on Knowledge and Data Engineering*, Part II, Vol. 11, No. 3, May/June 1999.
- [**PRD02**] C. Perkins, E. Royer, and S. Das, "Ad-Hoc On-Demand Distance Vector (AODV) Routing", *IETF Internet draft*, MANET working group, Jan. 2002, draft-ietf-manet-aodv-10.txt.
- [**SPH04**] P. Samar, M. Pearlman and Z. Haas, "Independent Zone Routing: An Adaptive Hybrid Routing Framework for Ad-Hoc Wireless Networks", *IEEE/ACM Transactions on Networking*, Vol. 12, No. 4, Aug. 2004.
- [**SWL04**] J. Song, V. Wong and V. Leung, "Efficient On-Demand Routing for Mobile Ad-Hoc Wireless Access Networks", *IEEE Journal of Selected Areas in Communications*, Vol. 22, No. 07, Sep. 2004.
- [**TCC06**] C. Tseng, H. Chen and K. Chen, "On the Distance Distribution of the Wireless Ad-Hoc Networks", *Proceedings of IEEE 63rd Vehicular Technology Conference*, Spring 2006.
- [**WEL02**] J. Wang, M. Elicin and J. Liu, "Multimedia Support for Wireless W-CDMA with Dynamic Spreading", *ACM Journal of Wireless Networks*, Vol. 8, 2002.
- [**WLC03**] J. Wang, J. Liu and Y. Cen, "Hand-off Algorithms in Dynamic Spreading WCDMA System Supporting Multimedia Traffic", *Special Issue on Recent Advances in Wireless Multimedia*, *IEEE Journal of Selected Areas in Communication*, Vol. 21, No. 10, Dec. 2003.
- [**XL04**] Y. Xiao and H. Li, "Local Data Control and Admission Control for QoS Support in Wireless Ad-Hoc Networks", *IEEE Transactions on Vehicular technology*, Vol. 53, No. 5, Sep. 2004.
- [**ZLGKMT**] C. Zhang, Y. Liu, W. Gong, J. Kurose, R. Moll, and D. Towsley, "On Optimal Routing with Multiple Traffic Matrices", *Proceedings of IEEE International Joint Conference of Computer and Communication Societies (INFOCOM)*, 2005.

