WLAN Multi-hop Throughput

Collaboration Projects

Analysis and Experiments on Throughput in Multi-hop WLAN Network

As basic research for improving voice quality in indoor communication by multi-hop WLAN connection, we conducted field experiments on a university campus and studied methods of determining throughput for connection control. This research was conducted jointly with the Graduate School of Advanced Integration Science (Professor Shiro Sakata and Assistant Professor Hiroo Sekiya), Chiba University.

Research Laboratories

Kengo Yagyu
Junichiro Hagiwara
Tomoyuki Ohya

1. Introduction

The use of WLAN in the construction of private networks in the home and in offices is growing. The issues involved in constructing a private network with a WLAN include efficient expansion of the area and eliminating dead zones[*1] caused by obstacles that block the signals. Multi-hop[*2] connection technology promises to solve those issues. The WLAN area can be expanded easily by installing WLAN Access Points (AP)[*3] that have the multi-hop function within an existing area (**Figure 1**). Such technology is in the process of being standardized by the Institute of Electrical and Electronics Engineers (IEEE) 802 Committee[*4] as IEEE 802.11s[*5] [1][2].

Progress is also being made in the use of voice communication as well as data communication over private networks. Specifically, the use of IP- Private Branch eXchange (PBX)[*6] and IP phone terminals for Voice over IP (VoIP) communication over private networks to build private telephone exchanges is increasing. In such cases, IP phone terminals that work with WLAN AP are used as private wireless phone networks. Furthermore, flexible network construction can be achieved by adding the WLAN multi-hop technology mentioned above.

When using a network for real-time communication such as VoIP, it is important to study communication quality.

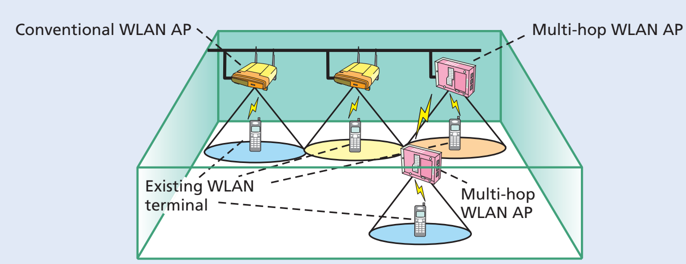

Figure 1 Expansion of WLAN area by multi-hop connection

*1 **Dead zone**: An area of poor radio signal reception caused by distance or blocking by buildings or other obstacles that prevents wireless communication.

*2 **Multi-hop**: A method for sending packets to a destination across multiple nodes (hopping).

*3 **WLAN AP**: A connection control node for adding a WLAN terminal to a network. It serves as intermediary for terminal communication, corresponding to a cell phone base station.

*4 **IEEE 802 Committee**: IEEE Committee that defines standards related to LAN and Metropolitan Area Network (MAN). Commonly known as LAN/MAN Standards Committee (LMSC).

*5 **IEEE 802.11s**: An international standard for multi-hop communication being settled by the IEEE 802 Committee.

*6 **PBX**: A private branch exchange node that manages internal voice calls and incoming and outgoing external calls.

There are limits on the accuracy of theoretical analysis of VoIP communication that involves multi-hop connections in a WLAN, and essentially no evaluation by field experiments has been done. Therefore experimental evaluation of the effects of interference between hops, which is an issue in WLAN multi-hop connections, on communication quality is required. It is also necessary to study connection control that guarantees quality by estimating the amount of traffic (maximum throughput) the network can accommodate and suppressing any communication beyond that amount [3].

In this article, we explain the results of evaluation by field experiments conducted on the campus of Chiba University and analysis of throughput with the objective of improving VoIP communication quality in multi-hop WLAN networks. This research was conducted jointly with the Graduate school of Advanced Integration Science, Chiba University, which has significant achievements in research related to multi-hop WLANs.

2. Quality Degradation due to Hidden Terminals and Improvement Method

The WLAN implements multiple access[*7] with the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA)[*8] method, so if multiple WLAN nodes exist, collision of simultaneously transmitted frames may occur statistically. Another problem in multi-hop communication is that simultaneous transmission with nodes that are outside the carrier sense range creates the hidden terminal[*9] problem of frame collision. The probability of collision naturally increases with the amount of traffic, and that causes degradation of quality in VoIP and other such User Datagram Protocol (UDP)[*10] communication that does not have congestion control.

In a Basic Service Set (BSS)[*11] WLAN of one AP and multiple terminals connecting to it, the network topology allows a maximum of two-hop wireless communication via the AP. Therefore, the hidden terminal problem can be averted by prior notification of the hidden terminal by virtual carrier sensing[*12]. For a multi-hop WLAN that involves three or more hops, however, virtual carrier sensing can bring about unfairness in transmission opportunities among terminals as well as the problem of exposed terminals[*13], which is a cause of reduced efficiency in radio frequency use. Virtual carrier sensing also requires low-rate transmission to allow reception by as many nearby nodes as possible. That is a burden on wireless resources in a high-speed WLAN that allows high-data-rate communication.

For that reason, we assume in the work reported here that virtual carrier sensing is not used in the multi-hop WLAN network. The specification for frame retransmission in the WLAN standards is to retransmit the frame a prescribed number of times in a short period of time following a communication error, and if there is success before that prescribed number of times has been exceeded, it is not regarded as a frame loss. We tried to improve communication quality by using that feature to estimate the amount of traffic that a network can handle and suppress the amount of network traffic to reduce the probability of frame collision due to hidden terminals and thus keep the number of retransmissions within the prescribed value.

3. Experimental Evaluation of Quality Degradation due to Hidden Terminals

We conducted field experiments to quantitatively measure WLAN multi-hop throughput to determine the effect of hidden terminals on communication quality. We set up multi-hop WLAN APs along an approximately 300 m passage of the Engineering Department building on the West Chiba Campus of Chiba University and conducted long hop experiments premised on area expansion. In the experiments, we used a prototype multi-hop WLAN APs developed by NTT DOCOMO (**Photo 1**) and measured end-to-end throughput

---

*7 **Multiple access**: Communication in which multiple nodes share same wireless resources. There are various methods for allocating individual wireless resources.

*8 **CSMA/CA**: A method of preventing collision in which a node first confirms that other nodes are not transmitting frames (carrier sensing) before transmitting.

*9 **Hidden terminal**: Terminals located in areas that cannot receive each other's signals nor determine the other's communication status.

*10 **UDP**: A low processing overhead transport layer protocol without delivery confirmation or congestion control. It is used in real-time communication when loss of data en route is not so important.

*11 **BSS**: A WLAN that has a star topology, in which there is a central station for controlling calls (AP) and all other terminals connect to that station.

*12 **Virtual carrier sensing**: A method that allows a node that is not reached by a direct signal from the transmitting node to detect that the medium is busy by notification sent from the receiving node to all of the nodes within its communication range.

*13 **Exposed terminal:** A terminal that is restraining transmission because a neighboring terminal is engaged in communication.

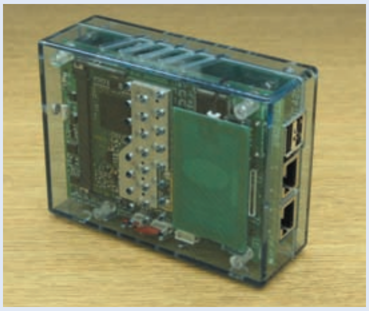

Photo 1 The prototype multi-hop WLAN AP

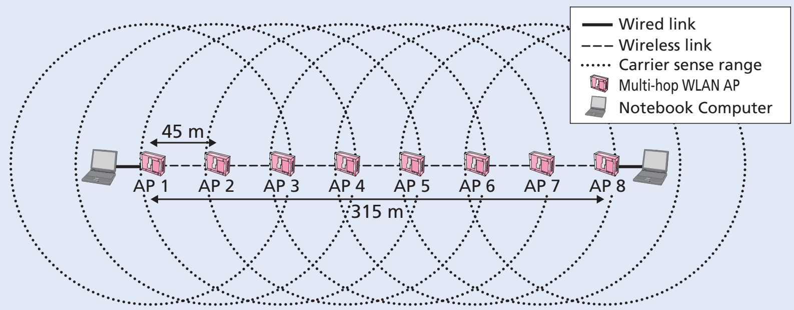

Figure 2 Experimental topology

with a seven-hop string (linear) topology (**Figure 2**). The main experimental specifications are shown in **Table 1**. For the application, we used 168 byte UDP/ Constant Bit Rate (CBR)[*14] traffic, assuming VoIP. The traffic was generated by unidirectional flow or bidirectional flow between notebook computers connected by wire to the both end APs of the multi-hop WLAN with the topology shown in Fig. 2. We varied the amount of traffic imposed on the network by changing the interval of data generation, and measured the changes in throughput. Concerning the transmisson reachable range and the carrier sense range, measurements made in preliminary experiments were described. The throughput measurements shown in **Figure 3** confirm a maximum bidirectional throughput of 0.68 Mbit/s for the assumed topology. That corresponds to accommodation of five simultaneous calls when using G.711[*15] VoIP. As we see in Table 1, the distance between AP is 45 m and the carrier sense range is 120 m, so simultaneous communication with the fourth-hop AP is possible (for example, simultaneous communication by AP1 and AP5 is possible). Also, for 168 byte data communication at the 18 Mbit/s physical layer rate, the single-hop throughput is 5.1 Mbit/s, so a simple calculation that does not assume hidden terminals should give a throughput of about 1/4 of that, or 1.3 Mbit/s. The difference between that calculated value and the value measured in the experiment is due mainly to the hidden terminal effect.

We also confirmed that throughput is particularly degraded in bidirectional flow with traffic overload (high traffic). This indicates that traffic overload may be a problem for VoIP, which is a UDP application with bidirectional communication. The reasons for the difference in throughput tendencies for bidirectional and unidirectional flow can be explained as follows. First, the flow of frames in the opposite direction in bidirectional flow generates frame retransmission due to collisions caused by hidden terminals, regardless of the amount of traffic. That consumes wireless

Table 1 Experimental specifications

Protocol	IEEE 802.11a (5 GHz band)
Frame payload	168 byte
Physical layer communication rate	18 Mbit/s
ACK communication rate	12 Mbit/s
Transmission buffer size	100 frame
Routing	Manual setup
Transmission reachable range	60 m
Carrier sense range	120 m
Inter-node distance	45 m

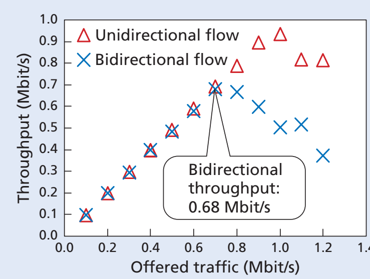

Figure 3 Experimental throughput measurements

*14 **CBR**: Communication in which frames are transmitted at fixed intervals (bit rate). Used for simulating voice communication or other fixed-rate communication.

*15 **G.711**: A standard specification for 64 kbit/s fixed bit rate voice encoding defined by International Telecommunication Union Telecommunication Standardization Sector (ITU-T) and used for transmitting voice signals in a fixed telephone network.

resources and decreases the traffic that can be accommodated. For unidirectional flow on the other hand, the interval of data generation is fixed, which is to say that there is no frame collision due to hidden terminals until the interval becomes shorter than the shortest interval in which there are no colliding frames within the carrier sense range. That allows a surplus of wireless resources and a greater amount of traffic can be accommodated.

4. Estimation of Maximum Throughput by Analysis

Here, we analyze bidirectional traffic flow on the basis of the field experiment results and explain the results of studying a method for estimating the amount of permissible traffic taking hidden terminals into account [4]. Because the hidden terminal problem decreases the amount of traffic that can be accommodated by a multi-hop WLAN network as described in Chapter 3 and because we can expect an increase in the amount of traffic that can be accommodated from the frequency reuse effect, which allows nodes that are outside the carrier sense range at the same time to communicate simultaneously, estimating the traffic capacity from the link speed specified by the WLAN alone is insufficiently accurate. We therefore studied in the work reported here a technique for estimating the permissible traffic that considers collision with hidden terminals and whether or not simultaneous transmission between nodes is possible.

Previous studies were limited to unidirectional flow to avoid increased computational and model complexity due to the complex topology. As a result, there are differences with an environment that assumes on-premises voice communication.

In this analysis, all terminals always have packets to be transmitted in their transmission buffers when the throughput is maximum. In other words, we assume that all terminals always have opportunity to transmit packets, so the probability of transmission is the same for all terminals.

First, we determined the collision patterns due to hidden terminals from the carrier sense range and communication range of each node in the topology. For bidirectional flow in the topology shown in Fig. 2, for example, collisions of data frame with data frame and data frame with ACK frame[*16] occur because of hidden terminals. We then calculated the probability of occurrence for each collision pattern to identify the bottleneck node in the network. The maximum throughput of the bottleneck node is the maximum throughput of the network. The maximum throughput of the bottleneck node can be calculated by subtracting the traffic calculated from the probability of collision from the node transmission traffic.

In **Table 2**, the results for the maximum throughput analysis for the topology shown in Fig. 2 are compared with the maximum throughput measurements from the experiments of Fig. 3. The analysis shows that accurate estimation of the maximum throughput when hidden terminals are present is possible. Sources of error include the effect of the beacon frame[*17] that is transmitted periodically by each AP and propagation error. The explanation here is for the example of a long-hop string topology, but this method is also applicable to various other topologies [5].

5. Conclusion

Assuming an environment for voice communication over a multi-hop WLAN , we analyzed bidirectional traffic throughput in a multi-hop environment for accurate estimation of the permissible amount of traffic and confirmed the approximate consistency of

Table 2 Comparison of throughput obtained by measurement and analysis

	Measured value (Mbit/s)	Value from analysis (Mbit/s)	Error (%)
Unidirectional flow	0.816	0.853	4.5
Bidirectional flow	0.680	0.757	11.3

*16 **ACK frame**: A receive confirmation frame sent from the receiving node back to the sending node when a data frame has been received successfully. ACK is short for Acknowledgement.

*17 **Beacon frame**: A frame that contains common information that is sent periodically from the AP to the terminals under its control and to surrounding nodes.

the result with experimental measurements. We also used an experimental device developed by NTT DOCOMO to make actual measurements, which validated the theoretical study and demonstrated the effectiveness in an actual environment.

In this research we also studied experimental verification of the number of VoIP terminals accommodated in a multi-hop WLAN at various other communication speeds [6] and the problem of unfairness arising for separated nodes that cannot decode the high-speed ACK frames in high-speed WLAN communication [7]. In future work, we will continue to study specific methods for application of the results of the theoretical analyses to connection control.

References

[1] S. Sakata, H. Aoki and K. Mase: "Mobile Ad Hoc Networks and Wireless LAN Mesh Networks," IEICE Journal, Vol. J89-B, No. 6, pp. 811-823, Jun. 2006.

[2] H. Aoki, et. al: "IEEE 802.11s Wireless LAN Mesh Network Technology," NTT DoCoMo Technical Journal, Vol. 8, No. 2, pp. 13-21, Sep. 2006.

[3] A. Fujiwara and T. Ohya: "Admission Control for VoIP Traffic in Wireless Mesh Networks," IEICE Technical Report, RCS 2006-93, pp. 205-208, Jun. 2006.

[4] M. Inaba, Y. Tomita, M. Matsumoto, H. Sekiya, T. Yahagi, S. Sakata, and K. Yagyu: "Analysis and Experiments of Maximum Throughput in Wireless Multi-hop Networks," IEICE Technical report, RCS 2007-121, pp. 55-60, Jun. 2007.

[5] M. Matsumoto, H. Sekiya, S. Sakata, T. Yahagi and K. Yagyu: "UDP Throughput Analysis of Bidirectional Flow for Wireless short-hop Networks," IEICE General Conference, Vol. B-21-25, pp. 626, Mar. 2008.

[6] Y. Tomita, H. Niida, M. Inaba, S. Sakata, H. Sekiya and K. Yagyu: "Experimental Verification of the VoIP Traffic Accommodation in Wireless LAN Mesh Networks," IEICE Society Conference, Vol. B-21-30, pp. 432, Sep. 2007.

[7] H. Niida, T. Nokphalinh, T. Fujiwara, H. Sekiya, S. Sakata, T. Yahagi, K. Yagyu and A. Fujiwara: "Unfairness Among Stations in Wireless LAN Mesh Networks," IEICE Technical Report, IN 2006-17, pp. 1-6, Jun. 2006.