Analysis of TCP/IP Communication using 384kbit/s-PHS Experimental System

FUMIHIDE KOJIMA†, YUKIYOSHI KAMIO†
AND MASAYUKI FUJISE†

A variety of mobile data communication services based on cellular phone and PHS (Personal Handy-phone System) have been developed and widely utilized. However, the maximum transmission speed is limited to 64 kbit/s in current public mobile data communication services. It is desired that higher transmission speed be supported in order to meet the requirement of mobile multimedia applications. For this reason, we have developed a 384kbit/s-PHS experimental system, which can achieve maximum transmission speed of 384 kbit/s by adopting the 64 kbit/s PHS data communication protocol (PIAFS) and the PPP Multilink protocol. This paper presents performance evaluation of the 384kbit/s-PHS experimental system. Throughput performance of the system is evaluated using FTP under various radio propagation environments. TCP behavior is investigated in evaluating the system.

384kbit/s-PHS 実験システムを用いた TCP/IP 通信の解析

児島史秀†　神尾享秀†　藤瀬雅行†

携帯電話や PHS (Personal Handy-phone System) をベースにした様々なモバイルデータ通信方式が開発され、広く使われている。しかしながら、現在の公衆データ通信サービスでは、最大通信速度は 64kbit/s が限度である。モバイルマルチメディアアプリケーションの要求を満たすためには、より高速な通信速度を実現することが望まれている。そこで筆者らは 384kbit/s-PHS 実験システムを開発した。本システムは 64kbit/s PHS データ通信プロトコル(PIAFS) と PPP マルチリンクプロトコルを用いて、最大 384kbit/s の通信速度を実現することが可能である。本稿では 384kbit/s-PHS 実験システムのパフォーマンスの評価について報告する。各種の伝搬環境の元で、FTP によるスループットの評価を行うとともに、TCP プロトコルの挙動について詳細に調査を行った。

1. Introduction

A variety of mobile data communication services based on cellular phone and PHS (Personal Handy-phone System) have been developed and widely utilized. However, the maximum transmission speed is limited to 64 kbit/s in current public mobile data communication services. It is desired that higher transmission speed be supported to meet the requirement of mobile multimedia applications such as real-time video transmission.

In order to realize high-speed mobile data communication system at reasonable cost, we have developed a 384kbit/s-PHS experimental system based on existing standards, infrastructures and devices for PHS [1]. This system can achieve maximum transmission speed of 384 kbit/s by using the 64 kbit/s PHS data communication protocol, which is known as PIAFS (PHS Internet Access Forum Standard) [2]. The PPP (Point-to-Point Protocol) Multilink protocol [3] is used to bundle six PHS connections to realize 384 kbit/s of bandwidth. Since this experimental system adopts existing standards and commercially available hardware and software, it can achieve high performance at low cost.

This paper presents detailed performance evaluation of the 384kbit/s-PHS experimental system. Throughput performance of the system is evaluated using FTP (File Transfer Protocol) under various radio propagation environments. TCP (Transmission Control Protocol) behavior is investigated in evaluating the system.

† Yokosuka Radio Communications Research Center, Communications Research Laboratory, Ministry of Posts and Telecommunications

2. Overview of System

Figure 1 shows the configuration of the 384kbit/s-PHS experimental system. This system has the following characteristics.

(1) In order to implement high performance system at reasonable cost, the experimental system adopts existing standards and commercially available devices as much as possible. For realizing compact and cost effective system, common devices and software are introduced whenever possible.

(2) In order to achieve 384 kbit/s of transmission speed without developing a proprietary protocol, six 64 kbit/s PHS circuits are bundled by the PPP Multilink protocol. The transmission speed can be changed in the range from 32 kbit/s up to 384 kbit/s by user requirement.

(3) Since three PHS basestation units are required to accommodate six 64 kbit/s PHS connections, interference of radio transmissions among basestation units should be avoided. The system supports a mechanism to synchronize transmission timing of PHS TDMA/TDD (Time Division Multiple Access / Time Division Duplex) frames.

(4) The experimental system provides Ethernet interfaces for both client terminals and server hosts in order for clients and servers to use the wireless link without introducing a special device or driver software.

(5) The experimental system supports graphical man-machine interface to facilitate controlling and managing the system.

This system consists of a base station and a mobile station. The base station has three PHS basestation units, each of which can accommodate two 64 kbit/s PHS radio circuits. It also includes an ISDN simulator, a base station control terminal and a network server host. The base station control terminal and the network server host are desktop PCs (Personal Computers) with Windows NT operating system. The base station control terminal is equipped with a multi-serial interface card, which supports eight RS-232C serial interface ports. Each of six serial ports of this interface card is connected to a 64-kbit/s TAP (Terminal Adapter for PIAFS), and each TAP is connected to a PHS basestation unit via the ISDN simulator. The base station control terminal manages PHS connections using the multi-serial interface card and supports routing function of IP (Internet Protcol) packets between PHS radio links and the Ethernet link in the base station. The network server host provides WWW (World Wide Web) server and FTP server functions that can be accessed from a mobile client.

The mobile station includes six PHS personal stations (mobile telephones), six 64-kbit/s TAPs, a mobile station control terminal and a client PC. Each of PHS mobile telephones is connected to a TAP. TAPs are connected to the mobile station control terminal, which has the multi-serial interface card as same as the base station control terminal. The mobile station control terminal is the same desktop PC as the base station control terminal, and supports IP routing function between PHS radio links and the Ethernet link in the mobile station. It also provides WWW-based man-machine interface for managing PHS connections. The client PC is a notebook PC with Windows 98 and can access to the network server host at the base station via wireless link. In this experimental system, Windows NT Server software is used as operating system for the base

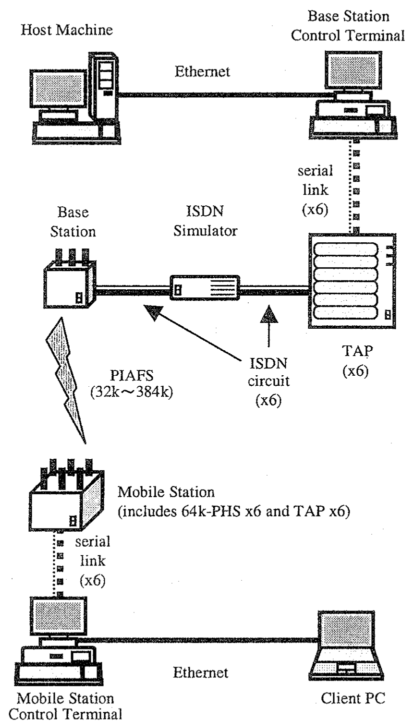


Fig. 1 System configuration

station control terminal, the mobile station control terminal and the network server host. The PPP and the PPP Multilink protocol functions are both supported by Windows NT operating system.

The radio frequency band used for this experimental system is assigned for private (non-public) PHS systems, and conforms to the ARIB (Association of Radio Industries and Businesses) standard RCR STD-28 [4]. Radio transmission power of the base station and the mobile station are both 10 mW. In order to avoid interference among different carriers, one of PHS basestation units has a role of master clock supplier for TDMA/TDD frames. Transmission frames of slave basestation units are synchronized by the master clock supplied by the master basestation unit.

3. Evaluation Procedure

We have evaluated our 384kbit/s-PHS experimental system basically from the following two viewpoints.

i) How TCP communication throughput is affected by the electric field strength of radio wave transmitted from the base station.

ii) How TCP communication throughput is affected when the number of underlying PHS connections is changed statically or dynamically.

As for the first viewpoint, the essential parameter for electric field strength is the distance between the base station and the mobile station. In addition, multipath fading is another important factor. Multipath fading is caused by interference of radio waves propagated via different paths due to reflection, diffraction and scattering.

As for the second viewpoint, the relationship between throughput performance and the number of PHS connections, we have performed two kinds of experiments. The one experiment is to change the number of PHS connections statically and the other is to change the number of PHS connections dynamically. In order to change the number of PHS connections dynamically, we have released one of six PHS connections manually while data transfer is in progress.

In order to inspect the influence of electric field strength to TCP throughput, we have performed measurement in both outdoor and indoor environments. The outdoor environment, a baseball ground, is nearly an open area where the influence of multipath fading is supposed to be relatively small. On the other hand, the indoor environment is supposed that many multipaths for radio wave propagation exist. For both environments, we first measured electric field strength at several points, chose throughput measurement points according to the obtained electric field strength values and then measured the FTP throughput. We transmitted a 1 Mbyte of data file for both directions, the direction from the base station to the mobile station (FTP Get) and the direction from the mobile station to the base station (FTP Put).

As for the evaluation about the relation between the throughput performance and the number of PHS connections, the experiment is performed in the indoor environment locating the mobile station at short distance from the base station where power loss and fluctuations of radio waves considered to be small. For the case where PHS connections are statically set, we measured the throughput for all cases from one PHS connection to six connections. For the case where the number of PHS connections is dynamically changed, we first started file transfer with setting up all six PHS connections and then released randomly selected one after about five seconds while the file transfer was going on.

For all experiments, we transmitted the same file for three times and calculated average throughput values for both FTP Get and FTP Put.

We also inspected PIAFS and TCP protocol behavior by capturing transmitted packets using the PIAFS monitor and the TCP analyzer. The PIAFS monitor captures all frames transmitted on a 64 kbit/s PHS circuit and can display logged frames indicating frame type, frame sequence number and CRC (Cyclic Redundancy Check) error. The TCP analyzer captures all packets transmitted on TCP connections setup between two hosts, and can analyze detailed behavior of TCP protocol sequence such as occurrence of retransmissions. In this experiment, the PIAFS monitor is connected to one of ISDN B-channels between the ISDN simulator and TAPs, and TCP analyzers are introduced on Ethernet links at both the base station and the mobile station.

4. Evaluation Results

4.1 Influence of Electric Field Strength

We first show the evaluation results from the viewpoint of relationship between electric field strength and file transfer throughput. In the following measurement results, the electric field strength values are averages of measured strengths of three PHS basestation units, and the throughput values for both of FTP Put and FTP Get are averages of three runs of measurements.

4.1.1 Indoor Environment

Table 1 shows file transfer throughput measured by locating the mobile station at several points with various distances from the base station in the indoor environment. In Table 1, we can observe that the throughput values at 10m point of FTP Get and 31.6m point of FTP Put are both under 190 kbit/s and exceptionally lower than other results. In these measurement points, it seems that there happened to exist multipath fading since a lot of people walked across the path between the base station and the mobile station in one of three measurement runs. The throughput of other two measurement runs was almost the same as the values obtained in the measurement at other points.

Figure 2 shows TCP and PIAFS packet sequences for the 31.6m point of FTP Put, which are obtained by the TCP analyzer and the PIAFS monitor respectively. In the PIAFS monitor result, TIME field indicates relative time slot number from the beginning of transmission, NUM filed indicates the send frame sequence number, and REQ filed indicates the requested sequence number which is expected to be received. Since PIAFS frame size is 640 bits and the circuit speed is 64 kbit/s, one time slot corresponds to 10 msec. In Fig. 2, the duration of the PIAFS sequence identified by [A] approximately corresponds to the duration [A] depicted on the TCP sequence. As

Table 1 Throughput measurement result (indoor environment)

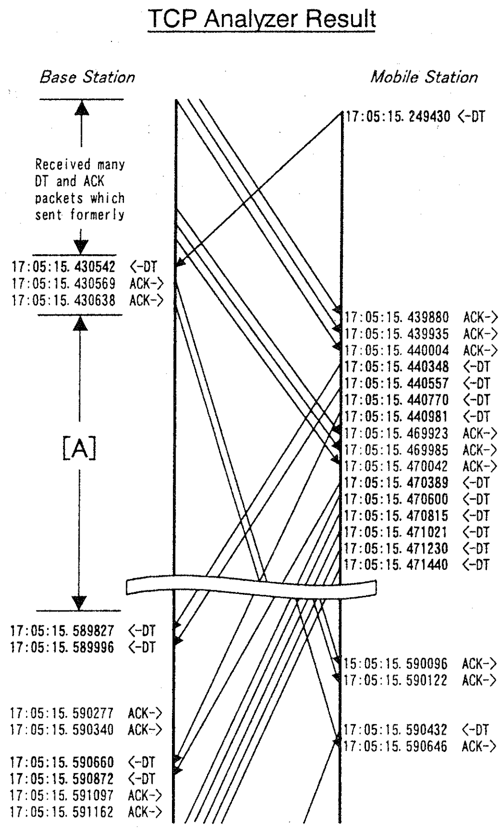
Distance from base station		10m	20m	26.4m	31.6m
FTP Get	Time (seconds)	40.75	26.97	27.96	29.60
	Throughput (kbit/s)	186.37	296.67	286.29	268.21
FTP Put	Time (seconds)	27.11	27.68	26.99	42.59
	Throughput (kbit/s)	295.17	289.60	296.43	189.84
Electric field strength (dBμV)		67.3	65.8	60.4	58.2

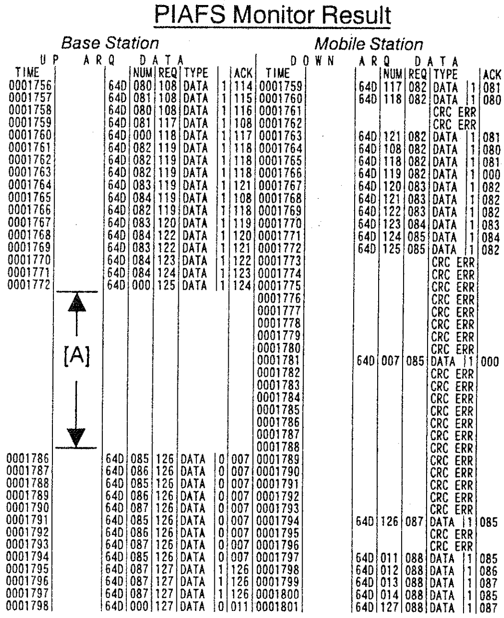
shown in Fig. 2, when many CRC errors are detected, retransmissions of TCP data segments are also observed. In TCP, the retransmission timeout (RTO) value is calculated by using measured round trip time (RTT), and RTO is increased according to the increment of measured RTT [5]. We have observed that, in our experiments, normal RTT value is about 150 msec by the TCP analyzer when neither CRC errors nor TCP retransmissions are detected. In Fig. 2, we can recognize that CRC errors continue for about 370 msec and this value obviously exceeds normal RTT value of TCP. We can conclude that TCP retransmissions are caused when recovery time from CRC errors at PIAFS level exceeds the TCP retransmission timeout value.

4.1.2 Outdoor Environment

This section presents the relationship between electric field strength and file transfer throughput measured in the outdoor environment. Figure 3 shows the case of FTP Get and Figure 4 shows the case of FTP Put. These figures indicate the throughput, the number of CRC errors and the number of TCP retransmissions. In the outdoor environment, we have performed measurements where electric field strength falls near 30 dBμV. At such points, it was hard to setup all six PHS connections.

As for the case of FTP Get, we obtained throughput values near 300 kbit/s and the throughput is not degraded when electric field strength keeps over 40 dBμV. In such cases, the PIAFS monitor detected no CRC errors. If we focus on the throughput values of FTP Put, however, they vary frequently and sometimes fall below 250 kbit/s even if the throughput values of FTP Get are stable when electric field strength is greater than 40 dBμV. For these measurement results, the PIAFS monitor detected no CRC errors but the TCP analyzer observed retransmissions about 10 to 70 segments as shown in Fig. 4. This unstable throughput fluctuation of FTP Put is caused by poor performance of the client PC (notebook PC with Windows 98) rather than radio wave propagation environment. For the case of FTP Get, since the client PC sends only small size of TCP ACKs (acknowledges), the throughput is not seriously affected by the poor performance of the client PC. But, in the case of FTP Put, the performance of the client PC is supposed to be a dominant factor of throughput degradation since the client PC must send a lot of data segments.





- The left side of this figure shows TCP retransmission sequence caused by PIAFS level CRC errors shown in the right side.
- Time values indicated by the PIAFS monitor are relative values from the start time of minitoring.
- The duration of the PIAFS sequence identified by [A] corresponds to the duration [A] on the TCP sequece.

Bold Fonts indicate retransmitted TCP packet.

Fig. 2 Typical example of TCP retransmission sequence

When the electric field strength is less than 40 dBμV, most of throughput values are degraded below 250 kbit/s for both FTP Get and FTP Put. As shown in Fig. 3 and Fig. 4, CRC errors and TCP retransmissions tend to increase when electric field strength is less than 40 dBμV. However, as shown in Fig. 3, there are some cases that no TCP retransmissions are observed even if CRC errors (40 to 90) are detected. In such cases, it is supposed that error recovery at the PIAFS level works well before TCP retransmission timer expires. If occurrences of CRC errors are not so many times and not burst, they will not give critical damage to TCP throughput. On the other hand, there are some cases where TCP retransmissions are observed and throughput is degraded even if no CRC errors are detected. In this experiment, since only one PIAFS monitor taps a specific PHS connection, it is possible that CRC errors on other PHS connections that are not inspected by the PIAFS monitor cause throughput degradation.

Another anomaly is that, in some cases, throughput keeps good value even though electric field strength is less than 40 dBμV. As explained before, electric field strengths shown in the figures are averages of three PHS basestation units. There are small differences of electric field strengths among those three basestation units. We observed that as the distance between the mobile station and the base station becomes longer, the difference of electric field strengths among three basestation units tends to be wider. For the case where the throughput is largely degraded, electric field strength of one of three PHS basestation units was less than 35 dBμV. On the other hand, the throughput keeps high average if electric field strengths from all of three basestation units are greater than 35 dBμV. If one of PHS connection is unstable, TCP/IP packets transmitted on this PHS connection will be lost or take long time to reach the receiver side. Even if data transmissions on other PHS connections have no problem, unstable situation of a specific PHS connection may give critical impact on throughput degradation.

If electric field strengths of all basestation units are less than 30 dBμV, it was impossible to setup six PHS connections. From the above experiment results, we can conclude that if electric field strengths of all three basestation units are greater than 35 dBμV and stable enough, the 384kbit/s-PHS experimental system can achieve high performance by TCP/IP.

In order to inspect TCP protocol behavior, we have analyzed the transition of TCP sequence

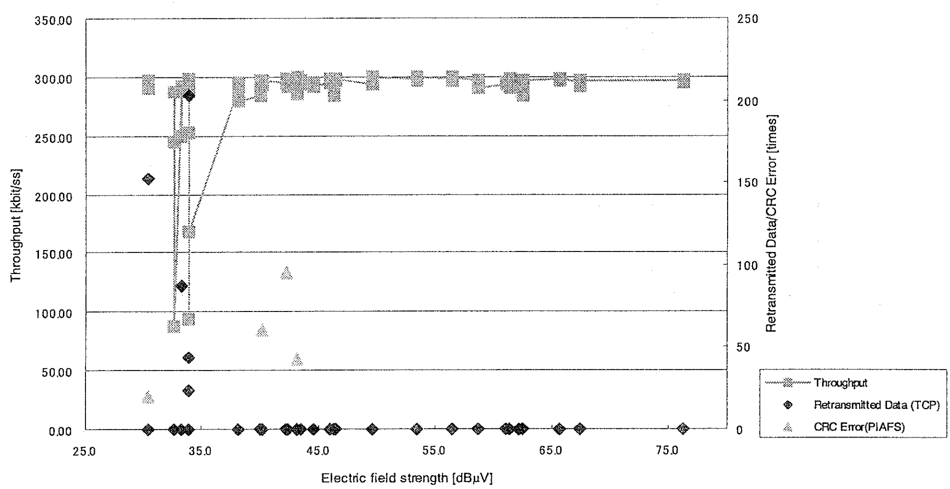


Fig. 3 Relationship between electric field strength and throughput and number of retransmissions (FTP Get)

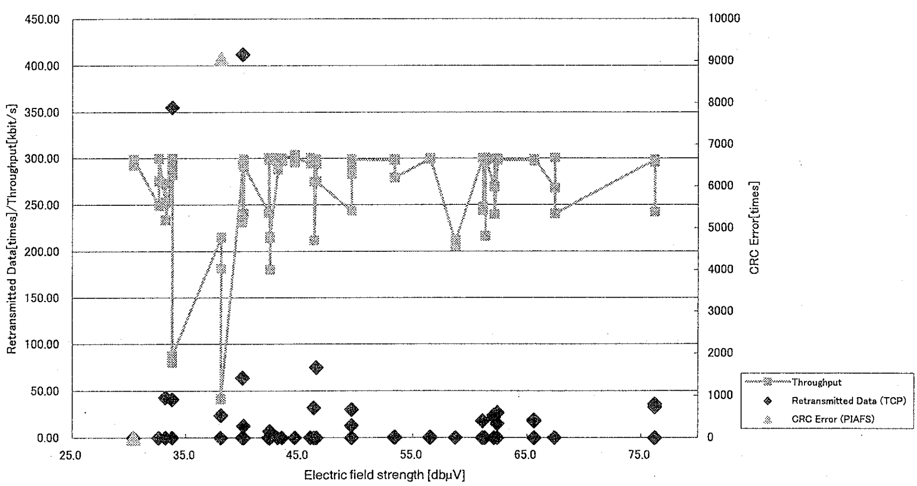


Fig. 4 Relationship between electric field strength and throughput and number of retransmissions (FTP Put)

number of data segments by using the TCP analyzer. A trace of TCP sequence number corresponds to a cumulative number of data bytes transferred. Figure 5 shows the transition of sequence number when no retransmissions are observed. Figure 6 shows the case when many retransmissions are detected and throughput performance is degraded. We can observe that when no retransmissions are detected, the sequence number increases linearly proportional to the transmission time. This result indicates that TCP data segments are transmitted efficiently without closing the send window.

On the other hand, as shown in Fig. 6, when retransmissions occurred, the sequence number does not increase for a long period. In TCP, when the data sender cannot receive a new ACK in the current retransmission timeout (RTO) period, the next retransmission is triggered and increments the RTO value (timer backoff). In addition, in current TCP implementation, the data sender decrements the send window size if segments are retransmitted and increments the send window size gradually by receiving new ACKs [5]. This procedure is known as the congestion avoidance algorithm since TCP considers that segments are lost due to network congestion. As in the case of Fig. 6, it takes long time to receive a new ACK so that the next timeout retransmission is triggered. Apparently, such timeout retransmissions and the congestion avoidance algorithm degrade the throughput performance seriously when segments are lost by circuit error.

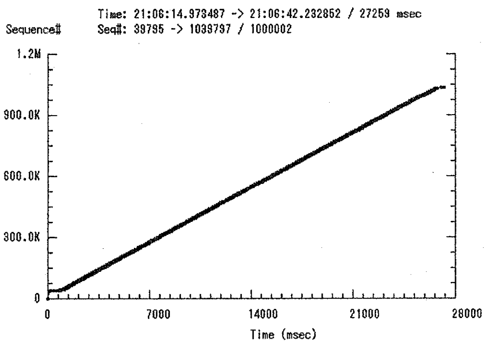


Fig. 5 Transition of TCP sequence number (When no retransmissions observed)

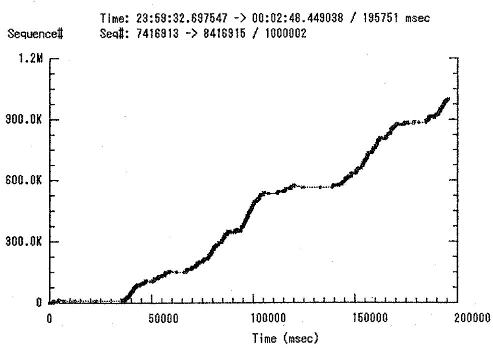


Fig. 6 Transition of TCP sequence number (When retransmissions observed)

4.2 Influence of Number of PHS Connections

4.2.1 Static change of PHS connections

Figure 7 shows the throughput measurement results in the case where the number of PHS connections is statically set while transferring a file. As show in Fig. 7, throughput values for both FTP Get and FTP Put are proportional to the number of PHS connections. Although neither CRC errors nor TCP retransmissions are observed in this experiment, throughput values for FTP Put are less than those values for FTP Get. This is because of the poor performance of the client PC as described before. For the case of FTP Get, we can obtain stable FTP throughput for any number of PHS connections.

4.2.2 Dynamic change of PHS connections

Table 2 shows the case when one of six PHS connections is released abruptly while file transfer is going on. It also shows average throughput values for the cases when the number of PHS connection is statically set to five and six.

In this experiment, we observed some TCP segments are lost by using the TCP analyzer. Figure 8 shows the transition of the TCP sequence number when one of six PHS connections is released. As shown in Fig. 8, when a PHS

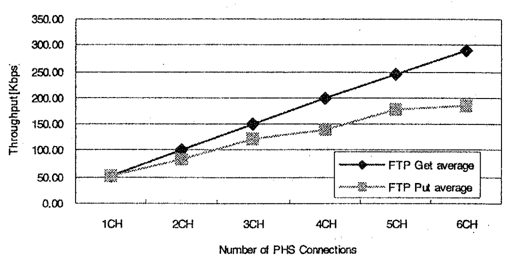


Fig. 7 Throughput measurement result (PHS connections statically changed)

Table 2 Throughput measurement result (PHS connections dynamically changed)

	FTP Get (kbit/s)	FTP Put (kbit/s)
Avg. 5CH	245.65	176.77
First	239.52	188.48
Second	178.08	159.20
Third	198.16	206.96
Avg. 6CH	291.09	186.64

connection is released, retransmission is triggered and the sequence number stops to increase. We can recognize that it takes a bit long periods to recover from the abrupt release of a PHS connection due to the backoff of retransmission timer value and the congestion avoidance algorithm of TCP as explained before.

We can see that there are differences among throughput values in Table 2. It is supposed that release timing of a PHS connection and its recovery timing are different for each file transfer run and that the duration for six connections and the duration for five connections are also different. This factor causes the difference of TCP protocol behavior and throughput values. Besides this, we observe that the throughput values of the first and third runs of FTP Put are higher than the average throughput of the case when six PHS connections are statically set. We obtained the average throughput of six connections by three runs of FTP Put. Due to poor performance of the client PC, the throughput of FTP Put was not stable for each run and throughput of two of three runs were lower than 180 kbit/s. In the case of FTP Put, as we mentioned before, performance of the client PC, such as busy condition of CPU, seems to cause the unstable throughput performance.

As shown in Table 2, when one of PHS connections is released while data transmission is in progress, the throughput is degraded and falls below even the case of five PHS connections. From the above results, it is turned out that total throughput obtained by the set of PHS connections is strongly affected by unstable situation of a specific PHS connection.

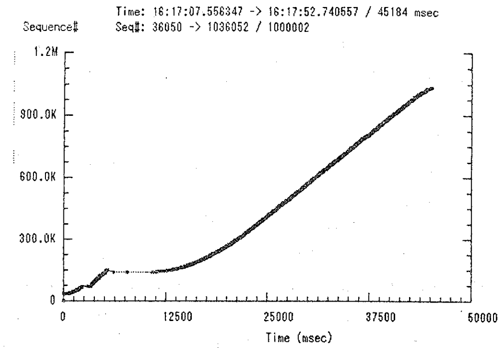


Fig. 8 Transition of TCP Sequence Number (When one of PHS connections released)

5. Conclusion

In this paper, we have presented implementation overview and performance evaluation of the 384kbit/s-PHS experimental system. The experimental system can achieve 384 kbit/s of transmission speed by bundling six PHS connections using the PPP Multilink protocol. Evaluation results of file transfer using FTP indicate that the system can achieve high average of throughput if the radio propagation environment is stable and the electric field strength is not less than 35 dBμV for all PHS basestation units.

However, if the radio propagation environment is unstable such as the case where many multipaths exist, and if many frame errors occur in burst, the roundtrip time in TCP level becomes longer and timeout retransmissions will be triggered. It seems that one of the reasons of throughput degradation is the fact that both TCP and PPP Multilink protocol are not designed to address the problem of frequent packet loss on circuits such as wireless links.

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