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File Transfers Over the GSM Network

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Abstract

Field experiments with vendor handsets, data cards, and several common file transfer protocols have been performed to assess the quality of GSM data services of the type "data circuit duplex asynchronous". File transfer times over many GSM-plus-PSTN links were measured and statistical performance figures for throughput, transmission efficiency, and network delay obtained. Surprisingly, best results were achieved with the "transparent" GSM 9.6 kbit/s data service and end-to-end retransmission. Although simple stop-and-wait protocols (XMODEM, YMODEM) did not perform well because of the large link delays, good throughput performance was obtained with sliding-window or other sophisticated retransmission schemes (KERMIT, ZMODEM). Even on very noisy links, throughput at 9.6 kbit/s was acceptable without a need for stepping down to 4.8 kbit/s or 2.4 kbit/s. Use of the "non-transparent" GSM data service, which protects the air link with the GSM built-in radio-link protocol (RLP), yielded no additional performance gains.

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I. Introduction

As the growth of remote-access computer applications continues, cellular carriers are being challenged to supply integrated data services. The European digital cellular telephone network, Global System for Mobile communications (GSM), provides “transparent” and “non-transparent” data services for rates between 600 and 9600 bit/s [1]. In transparent (T) mode, data transmission is protected against errors on the air link entirely by forward error correction (FEC) resulting in variable error rate, constant throughput, and fixed delay. The non-transparent (NT) data service additionally implements a Radio Link retransmission Protocol (RLP) to improve the quality of service. Thus transmission quality in terms of residual errors is constant and inherently better, at the expense of variable throughput and delay. The performance achieved by the respective data services will be investigated, especially under critical radio coverage conditions, i.e., at cell boundaries.

Although cellular mobile data has always been an integral part of the GSM specifications, it has taken several years for equipment manufacturers to come up with suitable hardware solutions to access these services and for the network operators to provide adequate coverage. Beginning in spring 1994, European network operators gradually made a basic set of GSM data services available for public use. Since the fall of 1995, the Swiss Telecom PTT has offered transparent and non-transparent “data circuit duplex asynchronous” bearer services at user rates 1.2 kbit/s, 2.4 kbit/s, 4.8 kbit/s, and 9.6 kbit/s in their GSM network (NATEL D). These current data services are based on a circuit-switched connection over the GSM cellular network and require call setups similar to the telephone system. Regarding data applications, GSM is thus best suited for sending and receiving large amounts of data infrequently, e.g., for downloading documents from a remote database.

Performance analysis will, therefore, concentrate on the transfer of files between a mobile computer terminal and a fixed host computer connected via modem to the Public Switched Telephone Network (PSTN). Of specific interest are field measurements of the time needed to establish the dial-up connection, the data rates that can be sustained during a file transfer at the different line speeds and for several common transfer protocols, and the round-trip delays across the networks involved in the connection. Because of the rather recent introduction of data services into GSM networks, few publications exist on related field experiments. Reference [2] reports measured performance of various file transfer protocols for asynchronous 9.6 kbit/s data transmission over the GSM network, however, the specific conditions of the GSM radio link were merely simulated by a traffic channel simulator. In [3] the performance of data transfers over the digital GSM network and over the analog Nordic Mobile Telephone (NMT) network is measured and compared but using only the non-transparent 9.6 kbit/s bearer service of GSM and applying to all file transfers exclusively the standard Transport Connection Protocol/Internet Protocol (TCP/IP) protocol suite. Finally, reference [4] describes data transmission experiments using the transparent 9.6 kbit/s bearer service of the DeTeMobil GSM network (D1) in Germany. However, no file transfer protocols were utilized and no call setup times, throughput or network delays measured because the emphasis of the work was on error statistics.

In this paper, results of a data transmission experiment are reported and analyzed which used the Swiss GSM network and appropriate vendor terminal adapters and communications software for file transfers between a mobile notebook PC and a host computer connected via modem to the fixed telephone network (PSTN). The next section describes the measurement setup and introduces the file transfer protocols applied for end-to-end data correction. Section III contains measurement results for various network configurations and transfer protocols. The important parameter round-trip delay is investigated in Section IV. Finally, a summary and several recommendations for using GSM data services efficiently are given in Section V.

II. Measurement Environment

Data transmission over GSM was demonstrated by Nokia at CeBit'94 with a notebook PC linked to their GSM phone via a credit card-sized PCMCIA module providing a 9.6 kbit/s interface to the GSM network. As early as the fall of 1993, Siemens had shown basic data functionality in an experiment involving a Siemens handy, a "Data-Service Adapter" (DSA) prototyped by Dr. Neuhaus, Hamburg, and a specially installed GSM base station. Today, several vendors offer similar "data cards" for the PCMCIA slot of notebook PCs, each card having a proprietary interface to their respective GSM telephone handset. Such data cards provide a digital communication link to the GSM network; the modulation/demodulation function towards the analog PSTN is part of the Mobile Switching Center (MSC) of the GSM network, where a modem pool in the Interworking Function (IWF) transfers the data over the public telephone network. A communications application on the notebook sees the card as the interface of a regular data modem, allowing file transfers to be performed using standard communications software.

A. Measurement Setup

Figure 1 shows the basic structure of the data transmission experiments reported in this paper. Mobile data terminal equipment DTEm is connected to the mobile station MS consisting of a data card DC connected to a handy phone HP with antenna. The GSM network is symbolized by a base station BS with antenna and a mobile switching center MSC housing the interworking function IWF

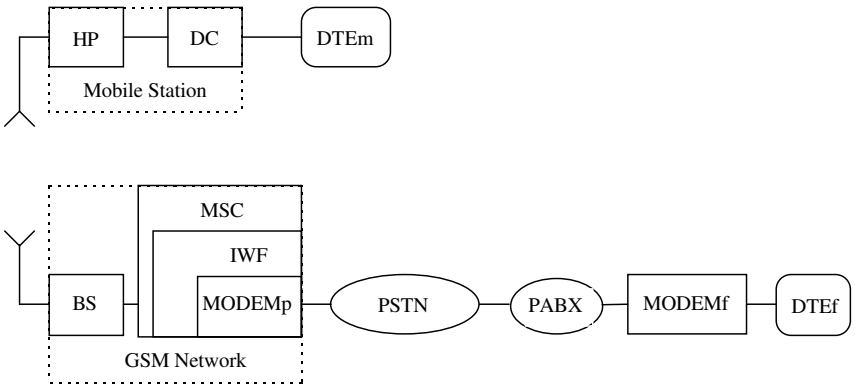

Figure 1: Basic arrangement of field experiments

with its pool of modems MODEMp. The public switched telephone network PSTN terminates at a local private automatic branch exchange (PABX), which connects to the fixed-line data terminal equipment DTEf via the fixed-line modem MODEMf.

Back when we ordered equipment for our field experiments, data cards supporting optionally both transparent (T) and non-transparent (NT) data delivery mechanisms were not yet available on the market. Consequently, two different DC/HP combinations had to be installed at the MS to support T and NT data services, the Siemens suite for transparent and the Nokia suite for non-transparent transmission. This is reflected in the list of equipment used for the experiments (see Table 1).

Block Fig. 1	Transparent Data Transmission	Non-Transparent Data Transmission
DTEm	IBM Thinkpad 750C (laptop) Intel486 SL 33 MHz MS-DOS 7.0 and Procomm Plus V2.01	IBM Thinkpad 750C (laptop) Intel486 SL 33 MHz MS-DOS 7.0 and Procomm Plus V2.01
DC	Siemens GSM Modem Card (PCMCIA card type 2)	Nokia Cellular Data Card DTP-2 (PCMCIA card type 2)
HP	Siemens S4 (GSM handy phone)	Nokia 2110 (GSM handy phone)
BS	Swiss Telecom PTT (NATEL D)	Swiss Telecom PTT (NATEL D)
MSC	Swiss Telecom PTT (NATEL D)	Swiss Telecom PTT (NATEL D)
MODEMp	V.22bis (2.4 kbit/s), V.32 (4.8 kbit/s and 9.6 kbit/s)	V.22bis (2.4 kbit/s), V.32 (4.8 kbit/s and 9.6 kbit/s), optional V.42 error correction
PSTN	Swiss Telecom PTT	Swiss Telecom PTT
PABX	Northern Telecom System SL/1	Northern Telecom System SL/1
MODEMf	Multitech Multimodem MT1432BAI, type selection according to MODEMp	Multitech Multimodem MT1432BAI, type selection according to MODEMp
DTEf	IBM PS/2-80 Type 8580-111 (PC) Intel386 20 MHz MS-DOS 7.0 and Procomm Plus V2.01	IBM PS/2-80 Type 8580-111 (PC) Intel386 20 MHz MS-DOS 7.0 and Procomm Plus V2.01

Table 1: Equipment used in the data transmission experiments (for blocks see Fig. 1)

In order to allow quantitative comparisons among results of field experiments performed with handsets from different vendors it must be guaranteed that their RF frontends are calibrated for equal sensitivity. Bit error rate (BER) measurements as a function of received signal power using a Rohde&Schwarz CRTP02 GSM Base Station Simulator revealed a 1 dB difference in sensitivity between Siemens and Nokia handies. For our field experiments this small difference was compensated by an attenuating antenna cable attached to the more susceptible Siemens handset.

B. File Transfer Protocols

When downloading or uploading a file via a transmission link between two computer systems specific communications software, the “file transfer protocol” (FTP), takes care of the details related to the file, e.g., filename and file size. Such FTPs can simultaneously provide end-to-end error detection and correction when sending or receiving files, i.e., the DTEs on either side of the transmission system (see Fig. 1) use sophisticated algorithms to make sure that the data received match the data sent. If a discrepancy is detected, the data is resent.

In all our measurements we use the popular communications software PROCOMM PLUS™ (Datastorm Technologies, Inc., Columbia, MO 65205, U.S.A.) which supports 15 standard FTPs mainly distinguished by the blocksize the files are segmented in for transmission and the automatic repeat request (ARQ) mechanism used for correcting erroneous blocks [5]. Table 2 gives an overview of all 15 file transport protocols and their main characteristics.

Protocol Name	**Blocksize**(byte)	**Error Check**	**Duplex Mode**	**ARQ Mechanism**
CIS B	512	CRC	half duplex	stop-and-wait
KERMIT	up to 1024	CRC/CS	full duplex	sliding window (14)
IMODEM	128	none	half duplex	streaming mode
MODEM7	128	CRC/CS	half duplex	stop-and-wait
SEALINK	128	CRC	full duplex	sliding window (6)
TELINK	128	CRC/CS	half duplex	stop-and-wait
ZMODEM	128 or 1024	32-bit CRC	full duplex	streaming or sliding w.
WXMODEM	128	CRC	full duplex	sliding window (4)
XMODEM	128	CRC/(CS)	half duplex	stop-and-wait
1KXMODEM	1024	CRC	half duplex	stop-and-wait
YMODEM	1024	CRC	half duplex	stop-and-wait
1KXMODEM-G	1024	none	half duplex	not applicable
YMODEM-G	1024	none	half duplex	not applicable
ASCII	not applicable	none	not applicable	not applicable
RASCII	not applicable	none	not applicable	not applicable

Table 2: Summary of file transfer protocols supported by PROCOMM PLUS™

FTPs use structured blocks consisting of various fields as basic units for data transfer. One field of width *blocksize* contains a segment of the file data. Other fields are necessary for sequencing the data segments and for detecting transmission errors. According to Table 2 error detection is usually accomplished by applying a 16 bit cyclic redundancy check (*CRC*) or a simple check sum (*CS*). In *stop-and-wait* ARQ the sending station transmits a single block and then awaits a response. No other data block can be sent until the receiver returns a positive acknowledgment (ACK) if the block is correct or a negative acknowledgment (NAK) otherwise. The *sliding window (N)* ARQ mechanism can have up to *N* blocks in transmission. If an erroneous block is detected, a NAK is returned and all following blocks are discarded at the receiving side until the contested block is correctly received. Thus the sending side must retransmit the erroneous block and all subsequent blocks ("Go-Back-N" protocol). In the more effective "selective repeat" protocol only the NAKed blocks are retransmitted. In the *streaming mode* ARQ technique no ACKs are returned unless an error is detected. In that case the receiving side sends a NAK, and the erroneous block is repeated by the sender. The transmission continues only after an ACK for the repeated block is received at the sending side.

C. File Characteristics

In order to separate data compression issues from the transmission problem analyzed here, "incompressible" files containing binary ONEs and ZEROs of equal probability were generated and used for the experiments. This random-data file definition on one hand frees us from using a larger collection of benchmark files, on the other hand we can create files of any specified length. Since most

of the FTPs considered (see Table 2) transmit file data in segments of either 128 or 1024 bytes, total file lengths were chosen to be an integer multiple of 1024 bytes. It will be assumed that FTPs not allowing their built-in data compression mode to be disabled (like the KERMIT implementation by PROCOMM PLUS™) do not modify the length of the described random-data files during transmission.

D. Quality of the Radio Link

Wireless communication over a mobile computer platform is sensitive to the environment in which the workstation is used. The RF field strength impinging on the antenna of the handy phone HP (see Fig. 1) depends on the distance from the strongest base station (BS), on geographical surroundings, buildings and the room environment. Signal reflections may impair the link quality even if the field strength is high. When the terminal is moving, handovers of the cellular system can cause errors and disconnections. The field experiments reported in the sequel were generally performed in a *stationary environment*, i.e., with the HP not moving. Field strengths were controlled and selected according to the number of marks visible on the display of the Nokia phone. Table 3 shows five link quality classifications from "very good" to "very bad" together with the corresponding number of marks visible on the Nokia phone display and the range of signal levels as calibrated via a Rohde&Schwarz CRTP02 GSM Base Station Simulator.

Signal Quality	**Nokia Marks**	**Signal Level** (dBm)
VERY GOOD	5	- 60.0 ... - 77.0
GOOD	4	- 77.1 ... - 92.7
MEDIUM	3	- 92.8 ... - 99.9
BAD	2	- 100.0 ... - 105.4
VERY BAD	1	- 105.5 ... - 109.2

Table 3: Link quality classifications

During field experiments a compatible link quality is maintained even in the case of slowly changing environmental conditions by using the same external antenna for NT and T transmissions and by frequently alternating between the Nokia and Siemens mobile station configurations during corresponding measurements.

III. Measurement Results

This section first gives results for the time it takes to set up a data call. It then describes the basic measurement procedure for evaluating GSM data services via file transfers and introduces a figure of merit for their performance. An initial field experiment allows the various file transfer protocols to be ranked according to performance and is used to reduce the number of available FTPs to a representative smaller set. Finally, detailed measurement results are given for this subset of FTPs assessing the data services currently offered by the Swiss GSM network over radio links of different quality.

A. Connection Establishment Time

Prior to performing a file transfer using the configuration described by Fig. 1 the circuit-switched connection between mobile and fixed DTEs has to be established. This is achieved by dial-up either from DTEm (mobile originated call, MOC) or from DTEf (mobile terminated call, MTC). MOC connection setup times were determined by measuring via software the elapsed time (in ms) from issuing the call command in the laptop (DTEm) to receiving the CONNECT message from the GSM network. All experiments were performed on a wireless link of *MEDIUM* quality (see Table 3) with the error-correcting protocols (V.42/MNP) between MODEMp and MODEMf disabled. The results listed in Table 2 as *mean value* ± *standard deviation* [seconds] are averaged over 15 successive dial-ups for each user rate. For the chosen link quality all call attempts were successful. Comparable connection establishment times were observed when calling from DTEf (MTC) by dialing specific subscriber numbers for each service (i.e., a GSM multi-numbering scheme is used in NATEL D).

GSM Data Service Mode	**2.4 kbit/s**	**4.8 kbit/s**	**9.6 kbit/s**
Transparent Data Transmission (T)	20.31 ± 1.72	25.42 ± 1.97	26.49 ± 1.77
Non-Transparent Data Transmission (NT)	16.10 ± 1.30	21.33 ± 1.42	23.52 ± 1.60

Table 4: Time in seconds for mobile originated connection establishment of GSM data services

Table 4 states that for all user rates it takes some 4 seconds longer to set up a T mode service than to connect to the corresponding NT service. Since for NT mode an additional protocol (RLP) has to be initialized we would have expected the opposite result. Seeking an explanation, one should remember that the two data services have been realized with different mobile stations DC/HP (see Table 1). In an additional series of experiments we roughly measured (using a stop watch) also the time between issuing a call at the mobile station and receiving the first ring alert on the display of the remote computer (DTEf). Predictably the resulting dial-up time turned out to be independent of user rate and amounted to 9 ± 3 seconds for the Siemens MS (T mode) and 7 ± 2 seconds for the Nokia MS (NT mode). Detailed analyses of the message exchange between MS and GSM network using a base station simulator (Rohde&Schwarz CRTP02) allowed us to associate these differing times with systematic differences in call-control protocol processing time between the mobile stations of Siemens and Nokia. For example, when receiving a Layer 3 GSM channel *Assignment Command* the Siemens MS returns the corresponding *DL-Establish-Ind* message some 400 ms later to the network than the Nokia station.

Connection establishment time as a function of user rate shows only minor differences between 4.8 and 9.6 kbit/s but significantly smaller values for rate 2.4 kbit/s (see Table 4). With dial-up time found to be independent of user rate, modem startup/handshaking must cause this variance. According to Table 1 the modem pool MODEMp provides two different modem types: V.22bis for rate 2.4 kbit/s and V.32 for both user rates 4.8 and 9.6 kbit/s. It is conceivable that starting a V.22bis modem takes less time than the more complex V.32 high-speed modem, thereby keeping the establishment time for 2.4 kbit/s connections smaller.

According to reference [3], measurements of a large ensemble of GSM data call attempts using similar Nokia equipment yielded 28 - 31 seconds for establishing a 9.6 kbit/s NT-mode data call. This significantly higher connection establishment time measured in [3] may be caused by additionally activating V.42bis error correction/data compaction and by providing the richer TCP/IP protocol stack in both DTEs.

B. Measurement Procedure

All measurements reported below consist of the following operational steps: (1) choosing a measurement location according to signal quality (see Table 3), (2) connecting the Siemens MS for transparent (T) or the Nokia MS for non-transparent (NT) data service to the mobile laptop DTEm (see Fig. 1 and Table 1), (3) selecting on the laptop a given file transfer protocol which matches the FTP currently installed and executing in server mode on the remote computer DTEf, (4) dialing from DTEm and establishing a connection to the remote computer (DTEf) with a given user rate and data format, (5) uploading from DTEm the reference file consisting of 4096 random bytes, (6) logging the time t_t required for transferring the file and the number n_r of retransmitted blocks, (7) repeating steps (5) and (6) another nine times, and (8) terminating the connection. For all transmissions the same *asynchronous data format* is selected consisting of one start bit, eight data bits, no parity bit, and one stop bit; the flow control mechanism is uniformly set to *hardware flow control* (RTS/CRT).

The time t_t necessary for transferring the reference file from DTEm to DTEf is measured with millisecond accuracy using a software timer on the laptop. This time includes the initial handshaking and end-of-transmission procedures defined by the specific FTP as well as storing the file on the hard disk of the remote computer. Note that for very long files the procedural overhead becomes negligible compared to the time required for transmitting the file contents. In field experiments involving wireless links, time t_t is a statistical variable and the mean value of 10 successive transfers of the same file is quoted as file transfer time T_t. The number n_r of retransmitted blocks is reported by the communications software upon completion of a file transfer; its average value N_r over all 10 file transfers serves as an indication of the quality of the connection and directly impacts T_t.

Performance of a given FTP will be quantified by the efficiency E defined as average effective throughput of 10 individual measurements normalized by the nominal user rate:

$$Efficiency[\%] = \frac{File_Size[\text{byte}] \times 8[\text{bit/byte}]}{Transfer_Time[\text{sec}] \times User_Rate[\text{bit/sec}]} \times 100$$

Efficiency is thus the percentage of the nominal link capacity actually used for the data transfer.

C. Choice of File Transfer Protocols

A first series of measurements evaluating all standard FTPs supported by PROCOMM PLUS™ was conducted with the objective to select a smaller number of representative protocols for further detailed analyses. In the arrangement shown in Fig. 1, T-mode transmission at 9.6 kbit/s was performed over a GOOD quality link (see Table 3); error-correcting protocols (V.42/MNP) on the fixed telephone-line link between MODEMp and MODEMf were disabled. Average file transfer times T_t were determined and the resulting efficiency values E in % are plotted in Figure 2 (the bars representing individual FTPs are arranged in the same order as in Table 2). Note that for all particular file transfers the number n_r of retransmissions was zero, indicating ideal transmission conditions and that none of the transmitted blocks were garbled on the *GOOD* quality radio link. Nevertheless, performance of the different FTPs (always using PROCOMM's respective default settings) shows rather wide variations with efficiencies E ranging from 13% to 55%.

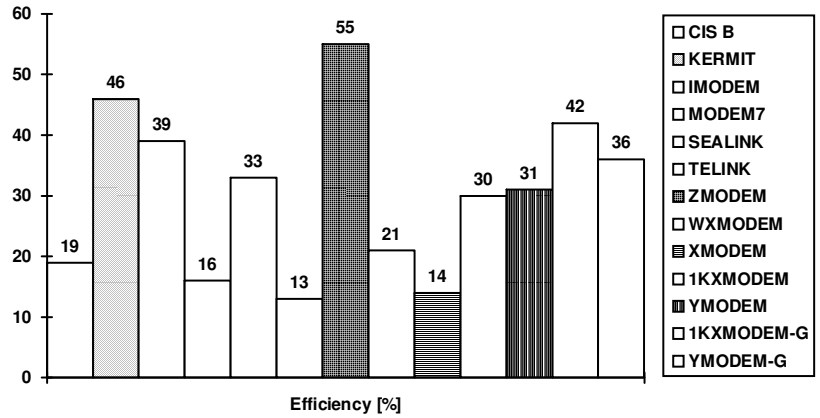

Figure 2: Performance of standard FTPs (see Table 2) using GSM transparent 9.6 kbit/s data services

File transfer protocols ZMODEM and KERMIT are the best performers according to Fig. 2 and will be put on the list for detailed studies. Protocols IMODEM, 1KXMODEM-G, and YMODEM-G achieve favorable performance figures but are inadequate for file transfers over unreliable data links since they do not implement error detection/correction (see Table 2); these three protocols, therefore, will not be considered further. SEALINK -- although having achieved a high rating in [2] -- and WXMODEM will be dropped from the list since both belong to the category *sliding window* ARQ but are clearly outperformed by KERMIT. The remaining six protocols all apply the *stop-and-wait* ARQ mechanism. With a blocksize of 128 bytes they achieve only very low efficiency which is roughly doubled by increasing the blocksize to 1024 bytes. As representatives of those two categories protocols XMODEM and YMODEM will be selected for further analyses since they are the best known in fixed-line modem communications.

Table 5 lists six file transfer protocols selected for more detailed measurements and contains some of their distinguishing characteristics. Note that the PROCOMM PLUS™ setup utility for protocol ZMODEM allows us to select three different ARQ methods when uploading a file: streaming, 2Kwindow, or 4Kwindow. Since according to Fig. 2 protocol ZMODEM is the most promising FTP, performance of all three ZMODEM versions will be evaluated in the following.

Protocol	**Short**	**Blocksize**(bytes)	**ARQ Mechanism**
XMODEM	X	128	stop-and-wait
YMODEM	Y	1024	stop-and-wait
KERMIT	K	20 ... 1024	sliding window (14) with selective repeat
ZMODEM	Z	subpackets 128 or 1024	streaming mode with go-back-N (*default option*)
ZMODEM_2K	Z2	subpackets 128 or 1024	sliding window (2048 bytes) with go-back-N
ZMODEM_4K	Z4	subpackets 128 or 1024	sliding window (4096 bytes) with go-back-N

Table 5: Names, short forms, and characterization of file transfer protocols studied in detail

D. Efficiency of File Transfers Over the GSM Network

An extensive measurement campaign has been carried out [6] for determining performance figures of the two GSM data transmission modes (T and NT) and three user data rates (2.4 kbit/s, 4.8 kbit/s, and 9.6 kbit/s) for file transfers from a mobile laptop to a computer connected to the PSTN as functions of the six FTPs listed in Table 5 and the quality of the intermediate air link (Table 3). All experiments used the arrangement shown in Fig. 1 with matching end-to-end FTPs executing in DTEm and DTEf. Additional error correction on the fixed telephone-line link was suppressed by disabling the V.42/MNP protocols in MODEMf and MODEMp. The measurement procedure described in Section III.B, which repeatedly transmits a unique file of length 4096 bytes containing random data, was used throughout.

The dependency of data transmission efficiency on the quality of the air link was studied using the definitions given in Table 3. Measurements at locations in the line-of-sight of a GSM base station activating all 5 marks on the Nokia phone (*VERY GOOD* link quality) were considered futile since a GOOD signal quality (4 Nokia marks) already warranted ideal wireless data transfers with zero retransmissions (see Section III.C). Locations with signal levels yielding MEDIUM or BAD link quality could be identified in shadowed regions. They allowed reliable connection setups and consistent operations. However, although measurement sites with *VERY BAD* link quality (only 1 mark visible on the Nokia display) were actually found near the cell boundaries of neighboring base stations, connections via the GSM network could rarely be established at these low signal levels, or they were interrupted so frequently that consistent measurements became impractical.

The measurement results are presented in three similar tables, one for each user rate. Efficiency E in %, standard deviation of 10 individual measurements, and the average number N_r of retransmissions per file transfer are listed side-by-side for T and NT transmissions. Note that N_r corresponds directly to the number of retransmitted blocks only in T mode and only for certain FTPs. For the family of ZMODEM protocols N_r gives the average number of error events (flagged by ** in Tables 6 - 8) which according to the implemented go-back-N scheme (see Table 5) may cause several blocks to be retransmitted and thus correspondingly decrease efficiency.

In the case of NT transmissions, non-zero values of N_r should rarely occur since the GSM-internal radio link protocol (RLP) corrects all transmission errors on the radio link, and errors on the fixed PSTN-PABX link are very unlikely. Therefore, retransmissions reported by the sender in the case of a *BAD*-quality radio link can be viewed as technical flaws and are flagged by * in Tables 6 - 8. It has been verified by additional experiments that these retransmissions are caused by time-outs of the sending FTP. The mobile transmitter does not receive an ACK in due time if, in the case of excessive noise on the air link, a block is frequently retransmitted inside RLP before it ultimately reaches the remote computer. Unfortunately, the PROCOMM software does not allow one to lengthen the corresponding time-out and the resulting end-to-end retransmissions in NT mode on noisy radio links will cause unnecessary overhead. The retransmitted blocks finally arrive as duplicates at the receiving side and must be discarded by the FTP.

Quality	**Transparent Data Transmission (T)**			**Non-Transparent Data Transmission(NT)**		
Protocol	*GOOD*	*MEDIUM*	*BAD*	*GOOD*	*MEDIUM*	*BAD*
X	$E = 35 \pm 1.4$ $N_r = 0$	$E = 34 \pm 0.8$ $N_r = 0.1$	$E = 33 \pm 1.0$ $N_r = 1.8$	$E = 23 \pm 1.6$ $N_r = 0$	$E = 21 \pm 1.5$ $N_r = 0$	$E = 19 \pm 1.4$ $N_r = 0.4$ *
Y	$E = 57 \pm 1.5$ $N_r = 0$	$E = 56 \pm 1.1$ $N_r = 0.2$	$E = 56 \pm 1.3$ $N_r = 2.7$	$E = 44 \pm 1.3$ $N_r = 0$	$E = 42 \pm 1.3$ $N_r = 0$	$E = 40 \pm 0.9$ $N_r = 0.7$ *
K	$E = 71 \pm 1.6$ $N_r = 0$	$E = 70 \pm 1.3$ $N_r = 0.3$	$E = 69 \pm 1.4$ $N_r = 2.5$	$E = 64 \pm 1.0$ $N_r = 0$	$E = 61 \pm 1.1$ $N_r = 0$	$E = 60 \pm 1.2$ $N_r = 0.3$ *
Z	$E = 88 \pm 1.5$ $N_r = 0$	$E = 87 \pm 1.1$ $N_r = 0.9$ **	$E = 86 \pm 1.4$ $N_r = 2.1$ **	$E = 81 \pm 1.1$ $N_r = 0$	$E = 78 \pm 1.0$ $N_r = 0$	$E = 77 \pm 0.9$ $N_r = 0.2$ *
Z2	$E = 86 \pm 1.4$ $N_r = 0$	$E = 85 \pm 1.0$ $N_r = 0.4$ **	$E = 85 \pm 1.3$ $N_r = 1.5$ **	$E = 80 \pm 1.0$ $N_r = 0$	$E = 78 \pm 0.9$ $N_r = 0$	$E = 76 \pm 1.1$ $N_r = 0.3$ *
Z4	$E = 87 \pm 1.4$ $N_r = 0$	$E = 86 \pm 1.4$ $N_r = 0.3$ **	$E = 86 \pm 1.2$ $N_r = 1.9$ **	$E = 81 \pm 0.9$ $N_r = 0$	$E = 77 \pm 1.1$ $N_r = 0$	$E = 75 \pm 0.8$ $N_r = 0.1$ *

*Table 6: Performance results at user rate **2.4 kbit/s** for different FTPs*

Quality	**Transparent Data Transmission (T)**			**Non-Transparent Data Transmission(NT)**		
Protocol	*GOOD*	*MEDIUM*	*BAD*	*GOOD*	*MEDIUM*	*BAD*
X	$E = 24 \pm 1.4$ $N_r = 0$	$E = 23 \pm 1.5$ $N_r = 0.3$	$E = 23 \pm 1.4$ $N_r = 1.9$	$E = 15 \pm 1.3$ $N_r = 0$	$E = 12 \pm 1.2$ $N_r = 0$	$E = 11 \pm 0.9$ $N_r = 0.5$ *
Y	$E = 46 \pm 1.7$ $N_r = 0$	$E = 45 \pm 1.5$ $N_r = 0.2$	$E = 45 \pm 0.8$ $N_r = 2.9$	$E = 37 \pm 1.1$ $N_r = 0$	$E = 33 \pm 1.1$ $N_r = 0$	$E = 31 \pm 0.9$ $N_r = 0.9$ *
K	$E = 63 \pm 1.4$ $N_r = 0$	$E = 61 \pm 1.4$ $N_r = 0.7$	$E = 60 \pm 1.3$ $N_r = 2.7$	$E = 56 \pm 1.5$ $N_r = 0$	$E = 52 \pm 1.3$ $N_r = 0$	$E = 50 \pm 1.7$ $N_r = 0.5$ *
Z	$E = 78 \pm 1.6$ $N_r = 0$	$E = 74 \pm 1.4$ $N_r = 0.5$ **	$E = 72 \pm 1.3$ $N_r = 2.3$ **	$E = 73 \pm 1.0$ $N_r = 0$	$E = 70 \pm 1.3$ $N_r = 0$	$E = 68 \pm 0.9$ $N_r = 0.3$ *
Z2	$E = 77 \pm 1.4$ $N_r = 0$	$E = 74 \pm 1.3$ $N_r = 0.4$ **	$E = 73 \pm 1.3$ $N_r = 1.7$ **	$E = 71 \pm 1.3$ $N_r = 0$	$E = 69 \pm 1.1$ $N_r = 0$	$E = 68 \pm 0.8$ $N_r = 0.4$ *
Z4	$E = 78 \pm 1.4$ $N_r = 0$	$E = 75 \pm 1.5$ $N_r = 0.5$ **	$E = 74 \pm 1.0$ $N_r = 1.8$ **	$E = 72 \pm 1.1$ $N_r = 0$	$E = 69 \pm 1.2$ $N_r = 0$	$E = 69 \pm 0.9$ $N_r = 0.2$ *

*Table 7: Performance results at user rate **4.8 kbit/s** for different FTPs*

Quality	**Transparent Data Transmission (T)**			**Non-Transparent Data Transmission(NT)**		
Protocol	*GOOD*	*MEDIUM*	*BAD*	*GOOD*	*MEDIUM*	*BAD*
X	$E = 14 \pm 1.7$ $N_r = 0$	$E = 12 \pm 1.5$ $N_r = 0.4$	$E = 11 \pm 1.0$ $N_r = 2.9$	$E = 9 \pm 1.4$ $N_r = 0$	$E = 8 \pm 1.1$ $N_r = 0$	$E = 8 \pm 0.9$ $N_r = 0.8$ *
Y	$E = 31 \pm 1.8$ $N_r = 0$	$E = 29 \pm 1.6$ $N_r = 0.4$	$E = 27 \pm 0.9$ $N_r = 3.8$	$E = 28 \pm 1.4$ $N_r = 0$	$E = 27 \pm 1.2$ $N_r = 0$	$E = 23 \pm 0.8$ $N_r = 1.1$ *
K	$E = 46 \pm 1.6$ $N_r = 0$	$E = 43 \pm 1.4$ $N_r = 0.2$	$E = 39 \pm 1.1$ $N_r = 3.2$	$E = 41 \pm 1.4$ $N_r = 0$	$E = 38 \pm 1.4$ $N_r = 0$	$E = 35 \pm 0.8$ $N_r = 0.6$ *
Z	$E = 55 \pm 1.6$ $N_r = 0$	$E = 52 \pm 1.7$ $N_r = 1.1$ **	$E = 46 \pm 0.9$ $N_r = 2.7$ **	$E = 52 \pm 1.3$ $N_r = 0$	$E = 47 \pm 1.3$ $N_r = 0$	$E = 42 \pm 1.0$ $N_r = 0.4$ *
Z2	$E = 53 \pm 1.5$ $N_r = 0$	$E = 50 \pm 1.4$ $N_r = 0.7$ **	$E = 40 \pm 0.9$ $N_r = 1.9$ **	$E = 51 \pm 1.4$ $N_r = 0$	$E = 44 \pm 1.2$ $N_r = 0$	$E = 37 \pm 1.1$ $N_r = 0.1$ *
Z4	$E = 55 \pm 1.4$ $N_r = 0$	$E = 51 \pm 1.4$ $N_r = 0.8$ **	$E = 42 \pm 0.9$ $N_r = 2.1$ **	$E = 51 \pm 1.3$ $N_r = 0$	$E = 47 \pm 1.3$ $N_r = 0$	$E = 39 \pm 1.2$ $N_r = 0.2$ *

*Table 8: Performance results at user rate **9.6 kbit/s** for different FTPs*

Initially concentrating on the influence of user rate on file transfer efficiency, it is evident from Tables 6 - 8 that efficiency E decreases with increasing user rate. This result is somewhat misleading and is an unpleasant side effect of normalization which eliminates the dimension of time. Since elapsed time for performing a file transfer is the ultimate yardstick to be minimized, one has to consider that transmission time is doubled for every halving of the user rate. Consequently, stepping down to a lower user rate is only advantageous if the efficiency at full rate drops below 50% and if simultaneously the efficiency at the half rate is around 100%. Analyzing the individual results of Tables 6 - 8 in detail, there exists only one single case for which file transfer time can be reduced by stepping down to a lower user rate: using XMODEM in T mode on a *BAD* link saves 1.35 s out of 31.03 s (= 4.35 %) when stepping down from 9.6 kbit/s to the more reliable 4.8 kbit/s user rate. Disregarding this single statistical exception it can be concluded from the measurements that file transfers should always be performed at the highest available user rate.

An interesting aspect of GSM user rates when exercising T-mode transmission is the fact that by appropriate (full-rate) channel coding, error performance is intrinsically improved from 0.3% via 0.01% to 0.001% when reducing the user rate from 9.6 kbit/s via 4.8 to 2.4 kbit/s [1]. This means that for a given link quality as defined in Table 3 lower user rates should tendentiously produce fewer retransmissions. Such a trend for transparent data transmission can actually be read from the Tables 6 - 8 when focusing on column BAD quality and the protocols X, Y, and K; to a lesser extent it already shows up for *MEDIUM* line quality. As deduced in the previous paragraph, this inherent improvement of link quality is, however, not great enough to make it worthwhile to step down to a lower user rate -- at least not for the magnitude of link impairments still allowing consistent measurements.

According to Tables 6 - 8 performance results for the three variants Z, Z2, and Z4 of file transfer protocol ZMODEM are almost indistinguishable, with the streaming-mode version Z generally outperforming the two sliding-window versions and Z4 being slightly better than Z2 due to its larger window size. Thus for subsequent comparisons only the results for Z, the standard ZMODEM of PROCOMM PLUS™, will be quoted.

Based on Tables 6 - 8, Figure 3 visualizes the measured file transfer efficiencies of the most popular FTPs achieved in T mode on *GOOD* quality links. Ranking of the four protocols is the same for all user rates: XMODEM lowest, followed by YMODEM, then KERMIT and finally ZMODEM

clearly outperforming the other FTPs. For all FTPs efficiency is reduced significantly when increasing the user rate. From the corresponding results in Tables 6 - 8 a more gradual albeit consistent decrease in efficiency is observed also with degrading quality of the wireless link.

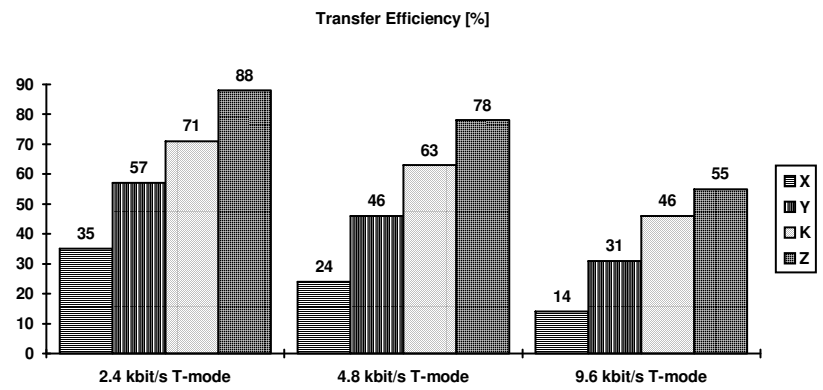

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*Figure 3: Performance of four popular FTPs (see Table 5) for GSM **transparent** data services*

Figure 4 reveals a similar behavior for NT-mode transmissions. Comparisons with Fig. 3 show, however, that performance is consistently inferior to the corresponding experiments in T mode. According to the measurement results of Tables 6 - 8 this finding also holds for degrading link quality. Even in the case of a *BAD* link which causes several end-to-end retransmissions in T mode, the inherently superior NT-mode service with its more efficient local RLP retransmissions never outperforms the transparent data service. By cross-checking with the results for *MEDIUM* quality of the air link it can be verified that this disappointing finding is not caused by the few unnecessary retransmissions on *BAD* links due to protocol time-outs (N_r flagged by *, see the discussion above).

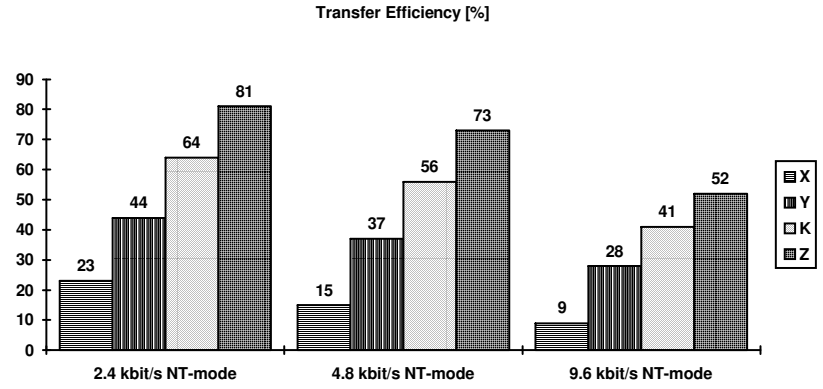

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*Figure 4: Performance of four popular FTPs (see Table 5) for GSM **non-transparent** data services*

E. Alternate Protocol Scenario for NT Data Services

It can be debated whether file transfers using the non-transparent GSM data services need a full-fledged FTP with end-to-end error correction although RLP already guarantees errorless transmission within the GSM network. The fixed-line sections consisting of PSTN and PABX (see Fig. 1) can be protected separately by activating V.42/MNP error correction capability between the modems

MODEMp and MODEMf. Protocol RASCII of the communications software PROCOMM PLUS™ (see Table 2) provides a completely transparent means to transfer binary files. In an alternate scenario for file transfers via GSM NT data services, transfer times were determined applying RASCII together with V.42/MNP but otherwise using the same measurement procedure as before (see III.B).

The resulting transfer efficiency $E \pm$ *standard deviation* in % is listed in Table 9 as a function of user rate and link quality (see Table 3). Except for a slightly higher efficiency at 9.6 kbit/s especially in a BAD air-link condition, performance is not improved compared to disabling V.42/MNP and using the autonomous end-to-end protocol ZMODEM (see Tables 6 - 8). Most disappointingly, transferring the reference file via the transparent data transmission services and applying ZMODEM generally yields better results, also at the highest user rate 9.6 kbit/s.

Link Quality	**Non-Transparent Data Transmission (NT)**		
User Rate	*GOOD*	*MEDIUM*	*BAD*
2.4 kbit/s	$E = 78 \pm 1.2$	$E = 73 \pm 1.2$	$E = 68 \pm 1.1$
4.8 kbit/s	$E = 65 \pm 0.8$	$E = 61 \pm 1.1$	$E = 57 \pm 1.2$
9.6 kbit/s	$E = 53 \pm 1.0$	$E = 49 \pm 0.9$	$E = 46 \pm 1.3$

Table 9: Performance results in NT mode for file transfers using RASCII+V.42/MNP protocols

F. File Transfers in Non-Stationary Environments

All measurement results reported so far have been achieved in a stationary radio environment, i.e., with the mobile station not moving (see also Section II.D). Although fixing the MS location allows accurate control of the field strength for comparative measurements, other characteristics of the mobile cellular radio channel, e.g., dynamic shadowing and handover, are not considered. The validity of the most important finding, i.e., that highest efficiency for file transfers is achieved with protocol ZMODEM using the transparent GSM data service, has been checked for true mobility by additional field experiments. In a hilly suburban terrain south of Zurich covered by three GSM base stations, a representative 45-km drive was selected which also included a stretch of the four-lane highway Zurich - Chur. The route was driven in a low traffic situation using a sedan automobile with GSM antenna mounted on the roof and the mobile station equipment (see Fig. 1) including an operator located on the rear seats.

With a single connection establishment to the remote host at departure time, a long reference file (131,0072 “random” bytes) was uploaded 11 times during the 40-minute drive. Respective transfer times t_t were continually logged together with corresponding error events n_r and position information. Two similar field experiments using protocol ZMODEM at a user rate of 9.6 kbit/s were performed consecutively on the same morning, one for T-mode and the other for NT-mode transmission. The results are listed in the first row of Table 10. The columns AVERAGE give the mean values of all 11 distinct measurements; the columns to the left and right are individual efficiencies for the shortest and the longest file transfer, respectively. For comparison, the second row of Table 10 contains corresponding results for a *GOOD* quality link from the earlier measurements in a stationary environment (see Section III.D, especially protocol Z in Table 8).

	Transparent Data Transmission (T)			Non-Transparent Data Transmission(NT)		
RF env.	min. transfer	AVERAGE	max.transfer	min. transfer	AVERAGE	max.transfer
mobile	e = 54.5 %	E = 53.1 %	e = 51.7 %	e = 51.9 %	E = 50.7 %	e = 49.8 %
static	e = 56.2 %	E = 55.0 %	e = 53.8 %	e = 53.3 %	E = 52.0 %	e = 51.1 %

Table 10: Performance results for ZMODEM at user rate 9.6 kbit/s in mobile and stationary environments

Transfer efficiency in a truly mobile environment turned out to be amazingly stable and consistent despite the numerous handovers observed during the drive. In the T-mode experiment, handovers inevitably caused retransmission events. Additional retransmissions were observed during high-speed driving on the highway. Nevertheless, throughout both 45-km test runs, neither of the two GSM-PSTN connections was ever dropped. Comparing this with the results in Table 8, equivalent link quality ranges between *GOOD* and *MEDIUM* on the average with both limits reached during extreme transfers. This is an indication that RF coverage along the total route is very well adjusted by the GSM operator. Last but not least, the results in Table 10 conclusively confirm that file transfers using T-mode transmission are more efficient than in NT-mode also in a very realistic mobile environment.

IV. Influence of Transmission Delay

Qualitatively, the results for the 9.6 kbit/s user rate reported in Section III (Fig. 2 and Table 8) compare well with the findings in reference [2]. Performance ranking among the key file transfer protocols XMODEM, YMODEM, KERMIT, and ZMODEM is identical and the effect of link quality on performance very similar. Generally, T mode transmission outperforms NT mode also according to the measurement results in [2] with the only exception of ZMODEM, where a slightly higher throughput with NT transmission is reported for a medium-quality link. Another qualitative difference exists for the SEALINK protocol, which in [2] ranks almost as high as ZMODEM, whereas the measurement results in Fig. 2 indicate a performance close to YMODEM.

Despite the good agreement in qualitative terms, the quantitative match of the measurement results reported in [2] with the corresponding numbers in Table 8 is very poor and needs explanation. As an example, for T mode transmission at 9.6 kbit/s over an errorless air link where according to Fig. 3 the four key FTPs X/Y/K/Z are ranked 14/31/46/55%, the consistently higher ranking 17/52/64/78% can be derived from the bar chart “Figure 4” given in [2]. Definition of “throughput” measured in [2] presumably corresponds to $E \times user_rate$ [bit/s] ÷ 100 of Table 8 and cannot explain the large numerical discrepancies. This leaves differences in transmission delay as a potential explanation since the sensitivity of file transfer protocols to round-trip delay of the transmission network is well known [2].

A. GSM Data Channel Delay

The GSM system employs sophisticated forward error correction (FEC) and interleaving in order to reduce the influence of air-link disturbances on the information transfer. Dependent on the GSM bearer service considered, these channel coding procedures and additional requirements for intermediate buffering of data create significant permanent transmission delays. Since references [1] and [2] quote very different numbers for the delay between terminal adaptation function (TAF) in the MS and interworking function (IWF) in the MSC (see Fig. 1) recourse is taken to GSM Rec. 03.05 [7] for calculating representative values for the GSM data services. According to [7] allocated delay allowances are either system or implementation dependent, therefore, the numbers given in Table 11 represent worst-case delay values fixing upper bounds for the implementation. The calculated round-trip delays are the sum of uplink and downlink delays; they assume perfect conditions on the radio path and do not include propagation delays. The range given is caused by the wide margin for

aligning the user data interface with the GSM frame structure. (The unresolved delay value *TL2runit* in NT mode represents the time in the transmit direction of TAF and IWF to convert the incoming user data bit stream into interpretable data units.)

User Rate	Transparent Data Transmission (T)	Non-Transparent Data Transmission (NT)
2.4 kbit/s	327.6 ... 336.8 ms	(channel not defined for NT transmission)
4.8 kbit/s	457.0 ... 466.2 ms	575.8 ... 585.0 ms + 2 × TL2runit
9.6 kbit/s	432.6 ... 441.8 ms	555.8 ... 565.0 ms + 2 × TL2runit

Table 11: Worst-case round-trip delays for different GSM bearer services (according to GSM 03.05)

The numbers in Table 11 manifest that round-trip delays are indeed different for the various GSM bearer services and considerably larger for NT than for T transmission. This finding contrasts with the choice of a fixed one-way transmission delay of 200 ms (i.e., conservative 400 ms round-trip) for the traffic channel simulator in [2] and may already explain some of the discrepancies with the results of our paper. Another source of additional delay is the PABX which is part of the arrangement in Fig. 1 but was not included in the test configuration of [2]. The following section describes an attempt to estimate delay values directly from file transfer experiments.

B. Delay Estimates from File Transfer Measurements

Simple stop-and-wait file transfer protocols like XMODEM and YMODEM are suitable for calculating delays across transmission links since their basic transfer mechanism of transmitting an information block and waiting for the acknowledgment is known and can be modeled quantitatively. Modeling is further simplified by choosing file lengths as integer multiples of the *blocksize* parameter and by providing errorless links where retransmissions cannot occur. Then total transfer time is proportional to file length except for an additive “overhead” time caused by initial and terminating information exchanges between the communicating protocol entities (see II.B). Assuming that this latter overhead is constant for a given protocol and transmission speed and also independent of file size, its duration can be estimated from measured transfer times of two (or more) files of different lengths. With known transmission times for information blocks and acknowledgments, round-trip delay can then be calculated.

The approach described was taken in [6] by transferring for each delay estimation three reference files of lengths 4096 bytes, 8192 bytes, and 16384 bytes made up of binary ONEs and ZEROs with equal probability. The three measured transfer times yield three estimates for the unknown overhead time, which were then averaged to form the final value. Individual experiments were performed using XMODEM and YMODEM protocols on a *GOOD* quality link following the measurement procedure described in Section III.B; V.42/MNP error control between MODEMp and MODEMf was always disabled. Considering the network structure shown in Fig. 1, the resulting round-trip delays represent the sum of individual delay contributions from the GSM network, PSTN, PABX, and MODEM processing.

In order to isolate distinct components of the overall round-trip delay, the arrangement in Fig. 1 was modified for measuring only the fixed-line sections of the transmission system. This was achieved by replacing the GSM data card (DC) in the mobile laptop by a fixed-line modem card (Nokia V.32bis Data/Fax Modem PCMCIA 2.0) and using it to emulate directly MODEMp functionality of the wireless setting. In this tethered arrangement modems MODEMp and MODEMf were under direct control and allowed three additional sets of experiments. In a first experiment the two telephone-line modems were connected back-to-back using minimum isolation circuitry. Round-trip delays were measured for the three user rates of interest according to the procedure described above. Protocols XMODEM and YMODEM yielded almost identical results which were then averaged to arrive at the delay estimates shown in column MODEM of Table 12. These values are reasonably small and reflect

the equivalent delays caused by protocol software execution and modem signal processing.

User Rate	MODEM	PABX	PSTN	GSM-T	GSM-NT
2.4 kbit/s	7	124	174	244	916
4.8 kbit/s	7	112	166	346	818
9.6 kbit/s	6	86	152	362	425

Table 12: Estimated round-trip delays in ms for the various network components of Fig. 1

The round-trip delay of the PABX network component was measured by a second experiment, which established a connection across the local PABX for file transfers between the MODEMp and MODEMf modems. Performing similar measurements as outlined above and subtracting the previously established MODEM delays, the results in column PABX of Table 12 were found. Note that the delay estimates increase with decreasing user rate. A similar trend is visible in the results obtained for the round-trip delays encountered in the public telephone network (column PSTN of Table 12). These latter delays were derived from a third set of measurements involving a fixed-line modem MODEMp attached to the mobile laptop. This time the connection of MODEMp was routed from a PABX subscriber line as an external call via the PSTN back to MODEMf on another port of the local PABX. The known contributions of MODEM and PABX to the overall transmission delay have been subtracted accordingly.

Establishment of round-trip delays for the three fixed-line segments of the arrangement in Fig. 1 allows us to complete Table 12 by entering the appropriately corrected results from the initial GSM round-trip delay experiments. For T-mode transmission the resulting delay estimates are well below the worst-case values of Table 11. The comparatively small round-trip delay for the GSM user rate 2.4 kbit/s is properly manifested by the estimate of Table 12, which amounts to some 75% of worst case. The measured round-trip delay for 4.8 kbit/s matches similarly well its worst-case allotment. In contrast, the delay found for 9.6 kbit/s transparent data transmission is quite large representing some 83% of the worst-case value given in Table 11. This inconsistency may be partly caused by the conspicuously small estimate of the corresponding PABX delay which biases the GSM results. The round-trip delay measured for NT data transmission at 9.6 kbit/s reaches also about 75% of the worst-case value given in Table 11 and thus represents a reasonable estimate. Unfortunately, this is not true for the two lower user rates where the measurements yield extremely large delays, well beyond the worst-case limits established in Table 11 for NT transmission. The massive disagreement cannot be explained, especially since the same measurement method was used throughout all experiments. One conclusion, however, can be drawn from the similarity between the delay estimates for 4.8 and 2.4 kbit/s NT transmissions: In the Swiss GSM network, the user rate 2.4 kbit/s, which according to [1] is not specified for NT mode, seems to use the same resources as 4.8 kbit/s.

Irrespective of certain inconsistencies in the measurement results of Table 12 there is sufficient evidence that the transmission delays in arrangement Fig. 1 are indeed larger than considered in [2]. Especially the delay of the fixed network cannot be neglected. The influence of transmission delay on the efficiency of file transfers is investigated in the next section, which will allow us to put the measurement results of [2] into proper perspective.

C. Efficiency as Function of Transmission Delay

File transfer protocols using the stop-and-wait ARQ mechanism can be expected to be very sensitive to transmission delay. These protocols stop sending after each block for the round-trip delay time until an acknowledgment is received. Complementing the GSM field experiments reported in Section III a series of corresponding measurements has been carried out [6] for the three modified network topologies described above (i.e., fixed-line network components MODEM, PABX, and PSTN) using a telephone-line modem instead of the GSM data card. Note that in all three fixed-line

networks our numerous file transfers have never experienced any retransmissions. In Fig. 5 efficiency *E* when applying protocol XMODEM for file transfers at the various user rates is plotted as a function of the respective round-trip delays (assembled from Table 12). The three performance values for GSM T-mode transmission over GOOD-quality links ($N_r = 0$) are taken from Table 6 - 8 and inserted in Fig. 5 at delays around 600 ms. The measurement point for 9.6 kbit/s at round-trip delay 400 ms is imported from reference [2].

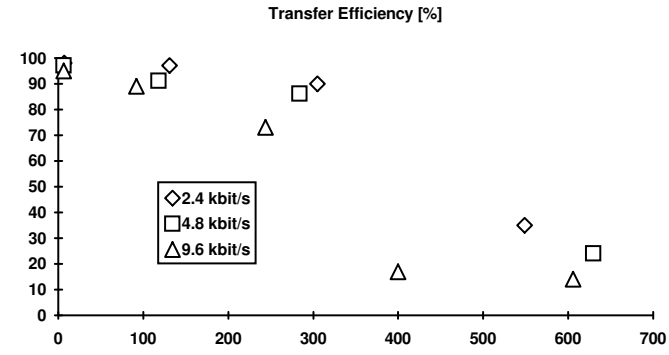

Figure 5: Performance of protocol XMODEM as a function of round-trip delay in ms

Figure 5 perfectly demonstrates the predicted strong decline of transfer efficiency with increasing transmission delay. The sensitivity is most pronounced for the highest user rate of 9.6 kbit/s where efficiency drops from 95% at 6 ms to 14% at 606 ms round-trip delay. The measurement value derived from [2] reflects an even more unfavorable dependency. Choosing a larger blocksize for the file data as in YMODEM (see Table 5) improves the throughput of the stop-and-wait class of FTPs, at least on good-quality links where no retransmissions occur. This is confirmed by the scatter plot in Fig. 6, where the values for T-mode transmission on GOOD quality links ($N_r = 0$) from Table 6 - 8 have been combined with the new fixed-line measurement results. Again transmission at 9.6 kbit/s suffers most from delays, however, overall performance is improved extending now from 97% at 6 ms to 31% at 606 ms round-trip delay. The 52% efficiency measured in [2] for a two-way delay of 400 ms fits quite well with the other results of Fig. 6.

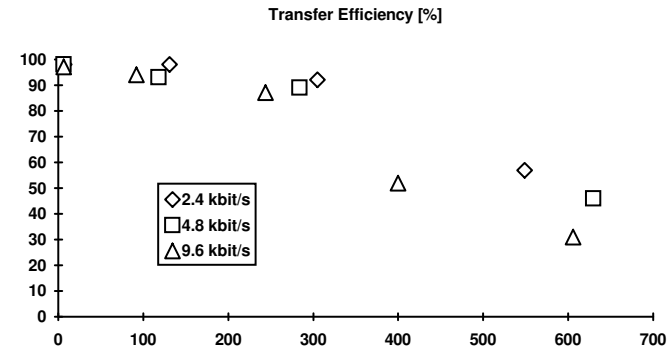

Figure 6: Performance of protocol YMODEM as a function of round-trip delay in ms

Figure 7 shows the results obtained with the most sophisticated streaming-mode protocol ZMODEM for errorless file transfers at different transmission delays. Transfer efficiency is less

affected by round-trip delays and now ranges from 99% at 6 ms to 55% at 606 ms for the highest user rate. The measurement E = 78% at 400 ms taken from [2] fits well into the plot for 9.6 kbit/s and strongly supports the notion that the round-trip delay chosen in [2] for simulating the GSM + PSTN network was overly optimistic.

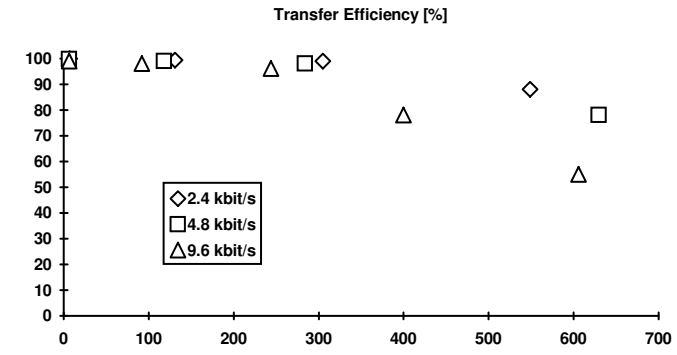

Figure 7: Performance of protocol ZMODEM as a function of round-trip delay in ms

D. Effect of Transmission Blocksize

Perfect knowledge of the information block, of file data and acknowledgment blocksizes, the ARQ mechanism, and the round-trip delay for a given FTP allow simulation of its behavior also in case of transmission errors. With all these parameters known or measured for XMODEM and YMODEM, file transfers of 4096 bytes assuming T-mode transmission at 9.6 kbit/s over a noisy link were simulated [6] using the Matlab tool. The two FTPs differ by their blocksizes used for transferring the file data (see Table 5). Large blocksizes are superior for high quality links, a small blocksize is advantageous on very bad transmission links where many retransmissions occur. The crossover point of transfer efficiency as a function of retransmissions due to erroneous information blocks is of specific interest and was simulated to occur at 20 retransmissions. Corresponding measurement results in Table 8 for T mode transmissions over the *BAD* quality link show only between 3 and 4 retransmissions on the average; the largest number of retransmissions ever measured with either protocol was n_r = 13 in this RF environment.

Thus simulations corroborate the experimental finding that YMODEM always outperforms XMODEM even on the worst-case *BAD* quality link which was selected to warrant consistent field measurements. The average number of retransmissions N_r = 20 necessary to reverse this behavior implies an air link of such inferior quality that according to the comments in Section III.D it cannot even sustain a reliable GSM connection setup.

V. Summary and Recommendations

Using two vendor handset/data-card combinations to access the asynchronous data services of the Swiss GSM network (NATEL D), field experiments were performed by transferring data files between a mobile PC laptop and a host computer connected via modem to the fixed-line telephone network (PABX/PSTN). Standard communications software PROCOMM PLUS™ was installed under MS-DOS in the two communicating computers allowing a wide selection of popular file transfer protocols (FTP). File transfer times and ancillary parameters were measured as functions of selected FTP, quality of intermediate air link, user data rate, and data service type. The results were analyzed statistically, yielding performance figures such as connection establishment time, transfer efficiency, throughput, number of retransmissions, and round-trip delay.

File transfer protocols using the simple stop-and-wait ARQ mechanism (like XMODEM and YMODEM) are unsuited for GSM-PSTN connections because the large overall network delay (up to 600 ms round-trip) reduces throughput dramatically. Protocols implementing sliding window ARQ or other sophisticated retransmission schemes (e.g., KERMIT and ZMODEM) are less sensitive to network delay and provide adequate performance also in situations of reduced radio coverage. Even on very noisy air links, transfer efficiency at the 9.6 kbit/s user rate is acceptable and cannot be improved by stepping down to the better protected transmission rates 4.8 kbit/s or 2.4 kbit/s. In radio environments allowing consistent field experiments without dropping the connection due to excessive perturbations, use of the “non-transparent” GSM data service, which protects the air link with the GSM-internal Radio Link Protocol (RLP), yields no additional performance gains. Throughput characteristics for downloading of files from the fixed host to the mobile computer are not different from uploading.

From the insight gained in our field experiments several fundamental recommendations can be formulated on the optimal usage of asynchronous GSM data services for file transfers involving the switched telephone network: (1) Position the mobile station in the RF environment such that at least two marks are visible on the field-strength display; (2) Select the highest possible GSM transmission rate; (3) Connect to “transparent” GSM data services (without Radio Link Protocol); (4) Activate the end-to-end file transfer protocol ZMODEM and select its (default) streaming-mode ARQ option; (5) Disable V.42/MNP error correction on the fixed-line telephone modem connecting the host computer. (Note that recommendations (1) and (4) are already included in the “User’s Guide for NATEL data” provided by the Swiss Telecom PTT [8].)

Most of the popular file transfer protocols are optimized to work on the fixed-line telephone network with lower transmission delay and lower error rate than experienced on a GSM-PSTN connection. FTP implementations in standard communications software usually do not allow changing critical parameters of the protocol for fine-tuning file transfer efficiency. Therefore, a serious effort should be undertaken to further optimize the most promising FTPs like ZMODEM and KERMIT for achieving even better throughput performance in the GSM data scenario.

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