Voice over ADSL

P. Michael Henderson
michael.henderson@cox.net

William Lipp
Lipp Service Consulting
w.b.lipp@ieee.org

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Voice over ADSL (VoADSL) is a hot topic of discussion in the communications industry, especially in the competitive local exchange (CLEC) market. CLECs envision providing a family of communications services, including local and long distance telephony and Internet access, to residential subscribers over a single twisted pair. Most of this discussion, however, has focused on the services and lower costs that could flow from competition by CLECs in the plain old telephone service (POTS) market. Missing from the dialog is a discussion of the feasibility of voice over ADSL – how many voice lines can be carried over a certain upstream data rate, and the delay that will be introduced.

This paper examines these questions. It specifically examines the questions of how many voice circuits can be carried over a certain bandwidth, the delay in the speech, and the effect of using some of the voice circuits for fax or data modem traffic.

VoADSL will be used to provision voice and data services for residential subscribers who need a limited number of voice lines. The exact number of lines required for residential service will vary by user and could range from one to perhaps five or six. For example, AT&T's cable division has specified a broadband telephony interface (BTI) unit that supports a maximum of four voice circuits. However, to allow for a sufficient range of services, this paper analyzes from one to ten voice circuits.

Provisioning will be similar to provisioning for voice over HDSL [HEN00]. ATM will likely be used as the low level protocol in order to provide a quality of service (QoS). A single ATM virtual circuit will be established between the integrated access device (IAD) in the home and a voice gateway device in the network for communicating voice cells. A second virtual circuit, or even multiple virtual circuits for supporting multiple service providers, will be established with the Internet infrastructure for data access See figure 1, next page.

Unlike VoHDSL, however, we are not attempting to maximize the number of voice circuits. Instead, we want to analyze the impact of operating a certain number of voice circuits over an ADSL line with a specified upstream bit rate. From this analysis, we want to answer the following questions:

1. What is the maximum number of voice circuits that can be provisioned over an ADSL line of a certain upstream bit rate, utilizing specified speech coders? In this analysis, we examine G.711, G.726 (32Kbps), G.728, and G.729.
2. On average, how much bandwidth is available for data while the specified number of voice circuits is active?
3. If everyone was speaking at the same time, how much bandwidth will be required for voice (what is the maximum bandwidth ever required for voice)? We do not wish to engineer the link to require discarding cells under the maximum load so this specification determines the limit for the number of voice circuits that can be supported.
4. How much one-way delay is introduced in the upstream channel in communicating voice over ADSL?

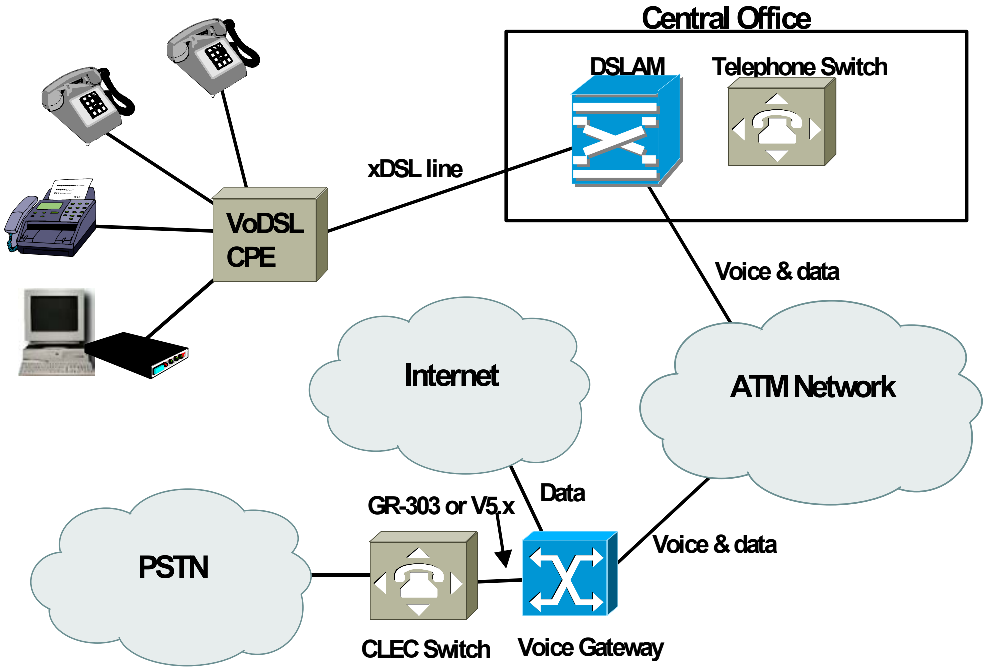

Figure 1: Network architecture for provisioning VoDSL. Note that the ATM cells simply flow through the DSLAM and are carried to the gateway over the ATM network.

ADSL is different from HDSL in that it implements asymmetric data rates, with the upstream much slower than the downstream. Because of this, the upstream channel becomes the limiting factor and determines the number of voice lines that can be serviced. But Internet access is also asymmetrical, with much more data flowing downstream than upstream. Because of this, we also analyze the performance of the downstream side of the link, particularly the average bandwidth available to data when different numbers of voice lines are active simultaneously. To avoid having the tables become too voluminous, we have established downstream/upstream data rates which are used for the analysis. The actual data rates achieved in practice may not be the same as we've chosen but these appear reasonable and can be used as guidelines. The downstream/upstream data rate pairs used in the analysis are shown in the following table.

Downstream data rate (Kbps)	Upstream data rate (Kbps)
384	128
512	192
768	256
1,024	320
1,024	384
1,544	512

Table 1: Downstream and upstream data rate pairs analyzed.

Since it appears that ATM will be used as the transport protocol for ADSL, we assume AAL2 cells carry the voice frames. AAL2 has a 47 octet payload while each speech frame carried in AAL2 has a 3 octet prefix. Voice frames can span multiple cells, without additional overhead.

ADSL has significantly more transmission delay than HDSL. ADSL has two transmission modes, a fast path and an interleaved path. The ITU G.992.1 recommendation specifies (§7.1.4) that the fast path delay shall not exceed 2 ms while the interleaved path delay shall be no more than:

$$t_d = 4 + (S - 1)/4 + S * D/4$$

where: t_d is the transmission delay in ms over the link
S is 1 for fast path and 1, 2, 4, 8 or 16 for the interleaved path.
D is 0 for fast path and 1, 2, 4, 8, 16, 32 or 64 for the interleave path

The ADSL interleaved path delays varies from 4.25 ms to 263.75 ms depending upon the interleaving. Since G.992.2 only supports interleaving, the minimum delay is 4.25 ms. This paper assumes that the voice is carried over the fast path and thus assumes 2 ms of one-way transmission delay. Since the ADSL delay is a constant, the reader may adjust for changes by simple addition or subtraction to the delay figures. Reed-Solomon error correction codes are utilized in the fast path so the only loss is some increased susceptibility to burst errors. This should have a minor impact on speech, since techniques for handling lost speech frames are available in essentially all modern speech coders.

In the real world, the upstream channel will probably be defined as a single fast path channel with all of the ATM cells, both AAL2 and AAL5 flowing through this single channel. In the downstream channel, the system designer has the flexibility of specifying a single fast path channel or specifying two channels, one interleaved for data and one fast path for voice. The calculations done in this paper assume a single downstream fast path, and thus will overstate the average downstream data bandwidth for systems with separate downstream channels. The round trip delay figures will likewise be optimistic if an interleaved channel is used downstream.

As in our earlier paper, we assume silence suppression is utilized. The voice model is the classical voice model with 352 ms average talkspurts, separated by 650 ms average of silence, with exponential distributions [BRA69].

The speech frame sizes utilized in the body of this paper are as follows: 20 octets for G.711 (2.5 ms of speech) except when G.711 is utilized for transporting fax or data modem traffic when 44 octet frames are used (5.5 ms), 20 octets for G.726 (5 ms of speech), 10 octets for G.728 (5 ms of speech), and 10 octets for G.729 (10 ms of speech). These frame sizes were chosen to minimize delay and the problem of clipped speech from the implementation of a synchronized speech coder (discussed below) combined with silence suppression. Short speech frames trade off bandwidth utilization for reduction in delay, but can reduce the number of voice circuits that can be implemented when the upstream bandwidth is severely limited. To determine this effect, Appendix A contains tables for G.711 and G.726 with 44 octet frames (5.5 ms of speech for G.711 and 11 ms of speech for G.726). Please see Appendix A for a discussion of the results from these longer speech frames.

Silence suppression is implemented on frame boundaries so only fixed sized frames are involved in the analysis.

The major innovation in the speech coder environment is our specification that the coders that encode speech in the upstream direction (from the subscriber to the network) are synchronized. That is, the frames of all of the active voice channels at the subscriber location are all output at the same time (when all are utilizing the same coder) or on specific boundaries when mixed coders are used. For example, if all the circuits were utilizing G.728, speech frames would be output to the AAL2 processor every 5 ms. If G.711 and G.728 coders were being utilized, the G.711 coder would output a frame every 2.5 ms while the G.728 coder would output its frames every other G.711 time. Assuming active speakers, at time 2.5 ms the AAL2 processor would see a G.711 frame of 20 octets. At time 5 ms, the AAL2 processor would see a 20 octet G.711 frame plus a 10 octet G.728 frame, etc.

The advantage of synchronizing the output of the speech coders is that the AAL2 processor does not have to wait to see if any additional speech frames are coming. Every 2.5, 5 or 10 ms the frames are there or they're not coming that period. If the cell is not full, the AAL2 processor pads it and immediately transmits it. This reduces delay[1].

It is fairly easy to synchronize the coders in the upstream direction since all the voice circuits can be implemented on a single digital signal processor (DSP). It may be harder to achieve this in the downstream direction but the higher speed of the downstream link mitigates the effect – it takes 3.3 ms to transmit a cell at 128 Kbps but less than 0.3 ms at 1.5 Mbps.

In our earlier [HEN00] paper we used queueing theory and simulation to analyze the capacity and performance of the system. In this system, queueing is not an issue because the ATM scheduler utilizes an algorithm which causes it to transmit the AAL2 voice cells as soon as they arrive – and since the speech coders are synchronized, all the cells which are going to arrive do arrive each period. The only queueing that occurs is when multiple cells arrive at the same time, but this waiting time is easy to calculate without resorting to queueing theory.

The problem is to calculate the expected number of cells. This can be done by calculating the probability, using the binominal distribution, of n speech samples being generated each period, where n varies from 0 to N, the number of voice circuits being analyzed. For each n, the number of cells required to carry the n speech frames is calculated and weighted by the probability of n. These are summed to obtain the expected number of cells transmitted each period. Multiplying by the number of periods per second and the number of bits in a cell (424) gives the expected bit rate per second for the voice.

All capacity calculations were performed using Excel spreadsheets. The standard deviations were calculated using MathCAD and are discussed later.

The analysis was performed for upstream line rates of 128 Kbps, 192 Kbps, 256 Kbps, 320 Kbps, 384 Kbps and 512 Kbps. Once a coder could support ten voice circuits, higher line rates were not analyzed. For example, G.729 can support ten voice circuits over only 128 Kbps. In this case, higher speed lines were not analyzed, although they would slightly reduce the one-way delay.

Delay is computed by summing the following sources of delay.

1. The first source of delay is the time required to buffer the block of speech. For example, G.711 buffers 2.5 ms of speech, while G.729 buffers 10 ms of speech.
2. Next, any processing time is added. G.711, G.726, and G.728 all process speech in very small increments so their contribution to delay is ignored. G.729, however, requires significant processing so 5 ms of delay is assumed.

[1] Phased speech frames have been suggested by the DSL Forum for systems without silence suppression. When silence suppression is implemented, however, the number of active speakers at any cycle is a probability function yielding 0 to N speech frames. Since we cannot know, a priori, the number of active speakers, or which voice lines will be active, we cannot implement phased speech coders with silence suppression.

3. Since we specified that the coders are synchronized, we assume no waiting delay to see if additional speech frames will arrive to fill an AAL2 cell.
4. No queueing delay is assumed because we specified that the line would only be loaded such that the maximum bandwidth required by the coders will not exceed the capacity of the line. We assume that the voice is given priority so that the next cell transmitted will be a voice cell, when one is ready to transmit.
5. Since an ATM cell could be in the process of transmission when the voice cell becomes ready, one cell transmission time is added as waiting time before the voice cell can begin transmission. In ATM, idle cells are transmitted to maintain synchronization when no data is available for transmission. Since we are interested in the worst-case delay, adding a full cell time is appropriate.
6. The time to transmit the voice cells is added. Note that this can be multiple cells if the number of speech frames output exceeds the capacity of a single AAL2 cell. For the delay calculations, the worst-case number of cells is used. This is the reason you may see the delay increase as the upstream bit rate and the number of lines supported increases. The higher upstream bit rate transmits the cells faster, but the number of cells to be transmitted also increases.
7. Transmission time over the link is assumed to be 2 ms, the ADSL fast path delay time.
8. For decode time, G.711, G.726, and G.728 are assumed to be zero while G.729 is assumed to be 5 ms.

The results of our analysis for voice channels only (no fax or data modem channels) are given in the tables below.

G.711

Downstream/ upstream bit rate (Kbps) - Upstream delay (ms) – Round trip delay (ms)	Voice circuits	Average voice bandwidth (Kbps)	Average downstream data bandwidth (Kbps)	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps)
384/128	Cannot support any voice circuits				Peak bandwidth for one line exceeds 128Kbps
512/192 8.92 15.07	1	59.6	452.4	132.4	169.6
	2	98.2	413.8	93.8	169.6
768/256 7.81 13.42	1	59.6	708.4	196.4	169.6
	2	98.2	669.8	157.8	169.6
1,024/320 7.15 12.48	1	59.6	964.4	260.4	169.6
	2	98.2	925.8	221.8	169.6
1,024/384 6.71 to 7.81 12.04 to 13.55	1	59.6	964.4	324.4	169.6
	2	98.2	925.8	285.8	169.6
	3	130.7	893.3	253.3	339.2
	4	161.2	862.8	222.8	339.2
1,544/512 6.16 to 7.81 11.21 to 13.41	1	59.6	1,484.4	452.4	169.6
	2	98.2	1,445.8	413.8	169.6
	3	130.7	1,413.3	381.3	339.2
	4	161.2	1,382.8	350.8	339.2
	5	191.3	1,352.7	320.7	508.8
	6	221.1	1,322.9	290.9	508.8

Table 2: Voice and data bit rates for G.711 coder and various downstream/upstream data rates.

G.726

Downstream/ upstream bit rate (Kbps) - Upstream delay (ms) – Round trip delay (ms)	Voice circuits	Average voice bandwidth (Kbps)	Average downstream data bandwidth (Kbps)	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps)
384/128 13.63 22.83	1	29.8	354.2	98.2	84.8
	2	49.1	334.9	78.9	84.8
512/192 11.42 to 13.63 20.07 to 23.11	1	29.8	482.2	162.2	84.8
	2	49.1	462.9	142.9	84.8
	3	65.3	446.7	126.7	169.6
	4	80.6	431.4	111.4	169.6
768/256 10.31 to 13.63 18.42 to 22.83	1	29.8	738.2	226.2	84.8
	2	49.1	718.9	206.9	84.8
	3	65.3	702.7	190.7	169.6
	4	80.6	687.4	175.4	169.6
	5	95.6	672.4	160.4	254.4
	6	110.6	657.4	145.4	254.4
1,024/320 9.65 to 12.30 17.48 to 20.96	1	29.8	994.2	290.2	84.8
	2	49.1	974.9	270.9	84.8
	3	65.3	958.7	254.7	169.6
	4	80.6	943.4	239.4	169.6
	5	95.6	928.4	224.4	254.4
	6	110.6	913.4	209.4	254.4
1,024/384 9.21 to 12.52 17.04 to 21.59	1	29.8	994.2	354.2	84.8
	2	49.1	974.9	334.9	84.8
	3	65.3	958.7	318.7	169.6
	4	80.6	943.4	303.4	169.6
	5	95.6	928.4	288.4	254.4
	6	110.6	913.4	273.4	254.4
	7	125.5	898.5	258.5	339.2
	8	140.4	883.6	243.6	339.2
1,544/512 8.66 to 11.97 16.21 to 20.62	1	29.8	1,514.2	482.2	84.8
	2	49.1	1,494.0	462.9	84.8
	3	65.3	1,478.7	446.7	169.6
	4	80.6	1,463.4	431.4	169.6
	5	95.6	1,448.4	415.4	254.4
	6	110.6	1,433.4	401.4	254.4
	7	125.5	1,418.5	386.5	339.2
	8	140.4	1,403.6	371.6	339.2
	9	155.3	1,388.7	356.7	424.0
	10	170.1	1,373.9	341.9	424.0

Table 3: Voice and data bit rates for G.726 coder and various downstream/upstream data rates.

G.728

Downstream/ upstream bit rate (Kbps) - Upstream delay (ms) – Round trip delay (ms)	Voice circuits	Average voice bandwidth (Kbps)	Average downstream data bandwidth (Kbps)	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps)
384/128 13.63 22.83	1	29.8	354.2	98.2	84.8
	2	49.1	334.9	78.9	84.8
	3	61.7	322.3	66.3	84.8
512/192 11.42 to 13.63 20.07 to 23.11	1	29.8	482.2	162.2	84.8
	2	49.1	462.9	142.9	84.8
	3	61.7	450.3	130.3	84.8
	4	71.1	440.9	120.9	169.6
	5	79.7	432.3	112.3	169.6
	6	88.6	423.4	103.4	169.6
	7	97.8	414.2	94.2	169.6
768/256 10.31 to 13.63 18.42 to 22.83	1	29.8	738.2	226.2	84.8
	2	49.1	718.9	206.9	84.8
	3	61.7	706.3	194.3	84.8
	4	71.1	696.9	184.9	169.6
	5	79.7	688.3	176.3	169.6
	6	88.6	679.4	167.4	169.6
	7	97.8	670.2	158.2	169.6
	8	107.3	660.7	148.7	254.4
	9	116.6	651.4	139.4	254.4
	10	125.6	642.4	130.4	254.4

Table 4: Voice and data bit rates for G.728 coder and various downstream/upstream data rates.

G.729

Downstream/ upstream bit rate (Kbps) - Upstream delay (ms) – Round trip delay (ms)	Voice circuits	Average voice bandwidth (Kbps)	Average downstream data bandwidth (Kbps)	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps)
384/128 28.63 to 35.25 52.83 to 61.67	1	14.9	369.1	113.1	42.4
	2	24.6	359.4	103.4	42.4
	3	30.8	353.2	97.2	42.4
	4	35.5	348.5	92.5	84.8
	5	39.9	344.1	88.1	84.8
	6	44.3	339.7	83.7	84.8
	7	48.9	335.1	79.1	84.8
	8	53.6	330.4	74.4	127.2
	9	58.3	325.7	69.7	127.2
	10	62.8	321.2	65.2	127.2

Table 5: Voice and data bit rates for G.729 coder and various downstream/upstream data rates.

For G.729, delay is highly dependent upon the number of lines active, although this effect decreases as the upstream bit rate increases. At 128 Kbps, with three lines the delay is 28.63 ms, from four to seven lines the delay is 31.94 ms, and from eight to ten lines the delay is 35.25. See the following table for all upstream line speeds (128, 192, 256, 320, 384 and 512 Kbps).

Line rate (Kbps)	Number of lines	Delay (ms)
128	1-3	28.63
	4-7	31.94
	8-10	35.25
192	1-3	26.42
	4-7	28.63
	8-10	30.83
256	1-3	25.31
	4-7	26.97
	8-10	28.63
320	1-3	24.65
	4-7	25.98
	8-10	27.30
384	1-3	24.21
	4-7	25.31
	8-10	26.42
512	1-3	23.66
	4-7	24.48
	8-10	25.31

Table 6: One-way delay for different upstream line rates and number of active voice circuits for G.729.

Handling fax and data modem calls

There are two ways to handle fax and data modem calls in a VoADSL environment: (1) switch to G.711 or (2) implement a "demod-remod" function. We will examine both approaches in turn, starting with the switch to G.711.

Switch to G.711

Switching to G.711 is the simplest approach and allows modulations such as V.90, which is sensitive to multiple conversions between analog and digital, to operate transparently.

The initial problem is to detect when a line is being used for a fax or data modem. Fax calls utilize calling tone which makes their detection easier. Data modems do not implement calling tone but the answer tone and/or training sequence can be detected. Since this paper is not about detecting fax or data modem calls, we will simply make the assumption that these calls can be detected and analyze the effect when the call is converted to G.711.

In all cases, we will limit the system to a maximum of two fax or data modem calls simultaneously. This seems reasonable given that the maximum number of lines is expected to be only four to six. Also, since the issue is the number of *simultaneous* fax/data modem calls, all of the lines could be fax lines (for example) but only two could be active simultaneously. Utilization of lines for fax operation is more likely than data modem operation since the ADSL line will provide a high speed connection to the Internet. We analyzed data modem operation primarily for completeness.

Fax and data modem operation is not as sensitive to delay as the human ear is to delay in voice – after all, fax and data modems are designed to operate over satellite links which introduce almost 250 ms of one-way delay. For this reason, and to minimize the impact on the average data bandwidth, we have chosen to use 44 octet frames for communication of the G.711 fax/data modem traffic.

These fax/data modem cells can be scheduled at a lower priority than the cells which contain the voice frames, thereby improving the delay characteristics of the voice circuits. While it is normally not possible to distinguish between AAL2 cells on a single virtual circuit, our system can distinguish between them, allowing this kind of priority scheduling in the upstream direction.

Mixing speech coders makes the analysis more complex since we will have different size speech frames entering the AAL2 processor at different time intervals. For example, if G.729 is used for voice and G.711 for fax/data modem calls, each active voice call will send a 10 octet frame to the AAL2 processor, every 10 ms. The G.711 coder, on the other hand, will send a 44 octet frame to the AAL2 processor every 5.5 ms.

Additionally, while the speech coders can implement silence suppression, the assumption is that the fax/data modem lines cannot. When computing the average arrival rate of cells into the ATM scheduler, these factors must be taken into account.

The results are presented for all the coders except G.711 (you can't switch to G.711 if you're already using G.711). For each line rate, results are shown for one fax/data modem line in operation and 2 fax/data modem lines in operation.

G.726

Upstream bit rate (Kbps)/ Delay (ms)	Simultaneous fax/data modem circuits	Voice circuits, including fax/data modem circuits	Average voice bandwidth (Kbps), excluding fax/data modem circuits	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem circuits
128	1	1	0.0	50.9	0.0
192 11.42	1	1	0.0	114.9	0.0
		2	29.8	85.1	84.8
		3	49.1	65.8	84.8
	2	2	0.0	37.8	0.0
256 10.31 to 11.97	1	1	0.0	178.9	0.0
		2	29.8	149.1	84.8
		3	49.1	129.8	84.8
		4	65.3	113.6	169.6
		5	80.6	98.3	169.6
	2	2	0.0	101.8	0.0
		3	29.8	72.0	84.8
		4	49.1	52.7	84.8
320 9.65 to 10.98	1	1	0.0	242.9	0.0
		2	29.8	213.1	84.8
		3	49.1	193.8	84.8
		4	65.3	177.6	169.6
		5	80.6	162.3	169.6
	2	2	0.0	165.8	0.0
		3	29.8	136.0	84.8
		4	49.1	116.7	84.8
384 9.21 to 11.42	1	1	0.0	306.9	0.0
		2	29.8	277.1	84.8
		3	49.1	257.8	84.8
		4	65.3	241.6	169.6
		5	80.6	226.3	169.6
		6	95.6	211.3	254.4
		7	110.6	196.4	254.4
	2	2	0.0	229.8	0.0
		3	29.8	200.0	84.8
		4	49.1	180.7	84.8
		5	65.3	164.5	169.6
		6	80.6	149.2	169.6

G.726 Continued

Upstream bit rate (Kbps)/ Delay (ms)	Simultaneous fax/data modem circuits	Voice circuits, including fax/data modem circuits	Average voice bandwidth (Kbps), excluding fax/data modem circuits	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem circuits
512 8.66 to 11.97	1	1	0.0	434.9	0.0
		2	29.8	405.1	84.8
		3	49.1	385.8	84.8
		4	65.3	369.6	169.6
		5	80.6	354.3	169.6
		6	95.6	339.3	254.4
		7	110.6	324.4	254.4
		8	125.5	309.4	339.2
		9	140.4	294.5	339.2
		10	155.3	279.7	424.0
	2	2	0.0	357.8	0.0
		3	29.8	328.0	84.8
		4	49.1	308.7	84.8
		5	65.3	292.5	169.6
		6	80.6	277.2	169.6
		7	95.6	262.2	254.4
		8	110.6	247.3	254.4
		9	125.5	232.4	339.2
		10	140.4	217.5	339.2

Table 7: Voice and data bit rates for G.726 coder and various downstream/upstream data rates, when one or two lines are switched to G.711 for fax or data modem traffic.

G.728

Upstream bit rate (Kbps)/ Delay (ms)	Simultaneous fax/data modem circuits	Voice circuits, including fax/data modem circuits	Average voice bandwidth (Kbps), excluding fax/data modem circuits	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem circuits
128	1	1	0.0	50.9	0.0
192 11.42	1	1	0.0	114.9	0.0
		2	29.8	85.1	84.8
		3	49.1	65.8	84.8
		4	61.7	53.3	84.8
	2	2	0.0	37.8	0.0
256 10.31 to 11.97	1	1	0.0	178.9	0.0
		2	29.8	149.1	84.8
		3	49.1	129.8	84.8
		4	61.7	117.3	84.8
		5	71.1	107.8	169.6
		6	79.7	99.2	169.6
		7	88.6	90.4	169.6
		8	97.8	81.1	169.6
	2	2	0.0	101.8	0.0
		3	29.8	72.0	84.8
		4	49.1	52.7	84.8
		5	61.7	40.2	84.8
320 9.65 to 10.98	1	1	0.0	242.9	0.0
		2	29.8	213.1	84.8
		3	49.1	193.8	84.8
		4	61.7	181.3	84.8
		5	71.1	171.8	169.6
		6	79.7	163.2	169.6
		7	88.6	154.4	169.6
		8	97.8	145.1	169.6
	2	2	0.0	165.8	0.0
		3	29.8	136.0	84.8
		4	49.1	116.7	84.8
		5	61.7	104.2	84.8

G.728 (continued)

Upstream bit rate (Kbps)/ Delay (ms)	Simultaneous fax/data modem circuits	Voice circuits, including fax/data modem circuits	Average voice bandwidth (Kbps), excluding fax/data modem circuits	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem circuits
384 9.21 to 11.42	1	1	0.0	306.9	0.0
		2	29.8	277.1	84.8
		3	49.1	257.8	84.8
		4	61.7	245.3	84.8
		5	71.1	235.8	169.6
		6	79.7	227.2	169.6
		7	88.6	218.4	169.6
		8	97.8	209.1	169.6
		9	107.3	199.6	254.4
		10	116.6	190.3	254.4
	2	2	0.0	229.8	0.0
		3	29.8	200.0	84.8
		4	49.1	180.7	84.8
		5	61.7	168.2	84.8
		6	71.1	158.7	169.6
		7	79.7	150.1	169.6
		8	88.6	141.3	169.6
		9	97.8	132.0	169.6

Table 8: Voice and data bit rates for G.728 coder and various downstream/upstream data rates, when one or two lines are switched to G.711 for fax or data modem traffic.

G.729

Upstream bit rate (Kbps)/ Delay (ms)	Simultaneous fax/data modem circuits	Voice circuits, including fax/data modem circuits	Average voice bandwidth (Kbps), excluding fax/data modem circuits	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem circuits
128 28.634	1	1	0.0	50.9	0.0
		2	14.9	36.0	42.4
		3	24.6	26.4	42.4
		4	30.8	20.1	42.4
192 26.42 to 28.63	1	1	0.0	114.9	0.0
		2	14.9	100.0	42.4
		3	24.6	90.4	42.4
		4	30.8	84.1	42.4
		5	35.5	79.4	84.8
		6	39.9	75.1	84.8
		7	44.3	70.6	84.8
		8	48.9	66.0	84.8
	2	2	0.0	37.8	0.0
256 25.31 to 28.63	1	1	0.0	178.9	0.0
		2	14.9	164.0	42.4
		3	24.6	154.4	42.4
		4	30.8	148.1	42.4
		5	35.5	143.4	84.8
		6	39.9	139.1	84.8
		7	44.3	134.6	84.8
		8	48.9	130.0	84.8
		9	53.6	125.3	127.2
		10	58.3	120.6	127.2
	2	2	0.0	101.8	0.0
		3	14.9	86.9	42.4
		4	24.6	77.3	42.4
		5	30.8	71.0	42.4
		6	35.5	66.3	84.8
		7	39.9	62.0	84.8
		8	44.3	57.5	84.8
		9	48.9	52.9	84.8

Table 9: Voice and data bit rates for G.729 coder and various downstream/upstream data rates, when one or two lines are switched to G.711 for fax or data modem traffic.

Implement Demod-Remod

When demod-remod is used, the same problems of detecting a fax or data modem call exist. Details of this detection are not covered here.

For fax or data modem calls, the following assumptions are made. For fax calls, the fax is assumed to operate at 14,400 bps. The fax digital data is packaged into AAL5 with a protocol data unit (PDU) size of 184 octets (this allows the PDU to fit into four ATM cells since eight octets are added to each PDU). Accounting for the overhead, communications of a single fax will require 16.59 Kbps. A data modem call is assumed to connect at 50 Kbps downstream, with an upstream data rate of 28.8 Kbps. Again, the PDU is assumed to be 184 octets. Accounting for the overhead, a single data modem call will require 33.18 Kbps upstream.

A fax communicates for relatively long periods of time when sending a page. Because of this, we assume that any fax call is constantly transmitting during the period of analysis. In most situations, a data modem is not transmitting continuously. Most people use a data modem for browsing the Internet, which causes bursts of data traffic, mostly in the downstream direction. The upstream direction usually is much less used. However, for analyzing the worst-case situation, we assume the data modem is constantly transmitting in the upstream direction during the period of analysis.

We limited our analysis to a maximum of two lines used for fax/data modem calls. There are five combinations of fax and data modem calls: (1) one fax call, (2) one data modem call, (3) two fax calls, (4) two data modem calls, and (5) one fax call plus one data modem call.

The analysis is performed by calculating the bandwidth required to carry the remaining voice calls – the bandwidth required to carry the fax and/or data modem calls is not included in the "Average voice bandwidth" or the "Peak voice bandwidth". The reason for removing the bandwidth for the fax and/or data modem calls is that the fax/data modem data is carried in separate ATM cells and does not have the latency requirements of the actual voice channels. When operating with demod-remod, the ATM scheduler priority is (1) actual voice channels, (2) fax/data modem demod-remod data, and (3) Internet data.

The calculations are only performed on combinations of speech coder and line rates that were calculated as feasible for voice only lines (the first calculations reported in this paper). What we are attempting to show is whether fax/data modem demod-remod can be used on those combinations, and what the effect will be on Internet data access.

G.726 (one fax line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 13.63	1	0	111.4	0
	2	29.8	81.6	84.8
192 11.42 to 13.63	1	0	175.4	0
	2	29.8	145.6	84.8
	3	49.1	126.3	84.8
	4	65.3	110.1	169.6
256 10.31 to 13.63	1	0	239.4	0
	2	29.8	209.6	84.8
	3	49.1	190.3	84.8
	4	65.3	174.1	169.6
	5	80.4	158.8	169.6
	6	95.6	143.8	254.6
320 9.65 to 12.30	1	0	303.4	0
	2	29.8	273.6	84.8
	3	49.1	254.3	84.8
	4	65.3	238.1	169.6
	5	80.4	222.8	169.6
	6	95.6	207.8	254.4
384 9.21 to 12.52	1	0	367.4	0
	2	29.8	337.6	84.8
	3	49.1	318.3	84.8
	4	65.3	302.1	169.6
	5	80.4	286.8	169.6
	6	95.6	271.8	254.4
	7	110.6	256.9	254.4
	8	125.5	241.9	339.2
512 8.66 to 11.97	1	0	495.4	0
	2	29.8	465.6	84.8
	3	49.1	446.3	84.8
	4	65.3	430.1	169.6
	5	80.4	414.8	169.6
	6	95.6	399.8	254.4
	7	110.6	384.9	254.4
	8	125.5	369.9	339.2
	9	140.4	355.0	339.2
	10	155.3	340.2	424.0

Table 10: Voice and data bit rates for G.726 coder and various downstream/upstream data rates, when one line is handling fax traffic using demod-remod.

G.726 (two fax lines)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128	1			
	2	0	94.8	0
192 11.42	1			
	2	0	158.8	0
	3	29.8	129.0	84.8
	4	49.1	109.7	84.8
256 10.31 to 11.97	1			
	2	0	222.8	0
	3	29.8	193.0	84.8
	4	49.1	173.7	84.8
	5	65.3	157.5	169.6
	6	80.6	142.2	169.6
320 9.65 to 10.98	1			
	2	0	268.8	0
	3	29.8	257.0	84.8
	4	49.1	237.7	84.8
	5	65.3	221.5	169.6
	6	80.6	206.2	169.6
384 9.21 to 11.42	1			
	2	0	350.8	0
	3	29.8	321.0	84.8
	4	49.1	301.7	84.8
	5	65.3	285.5	169.6
	6	80.6	270.2	169.6
	7	95.6	255.2	254.4
	8	110.6	240.3	254.4
512 8.66 to 11.14	1			
	2	0	478.8	0
	3	29.8	449.0	84.8
	4	49.1	429.7	84.8
	5	65.3	413.5	169.6
	6	80.4	398.2	169.6
	7	95.6	383.2	254.4
	8	110.6	368.3	254.4
	9	125.5	353.4	339.2
	10	140.4	338.5	339.2

Table 11: Voice and data bit rates for G.726 coder and various downstream/upstream data rates, when two lines are handling fax traffic using demod-remod.

G.726 (one data modem line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 13.63	1	0	94.8	0
	2	29.8	65.0	84.8
192 11.42 to 12.63	1	0	158.8	0
	2	29.8	129.0	84.8
	3	49.1	109.7	84.4
	4	65.3	93.5	169.6
256 10.31 to 13.63	1	0	222.8	0
	2	29.8	193.0	84.8
	3	49.1	173.7	84.8
	4	65.3	157.5	169.6
	5	80.6	142.2	169.6
	6	95.6	127.2	254.4
320 9.65 to 12.30	1	0	286.8	0
	2	29.8	257.0	84.8
	3	49.1	237.7	84.8
	4	65.3	221.5	169.6
	5	80.6	206.2	169.6
	6	95.6	191.2	254.4
384 9.21 to 12.52	1	0	350.8	0
	2	29.8	321.0	84.8
	3	49.1	301.7	84.8
	4	65.3	285.5	169.6
	5	80.6	270.2	169.6
	6	95.6	255.2	254.4
	7	110.6	240.3	254.4
	8	125.5	225.4	339.2
512 8.66 to 11.97	1	0	478.8	0
	2	29.8	449.0	84.8
	3	49.1	429.7	84.8
	4	65.3	413.5	169.6
	5	80.4	398.2	169.6
	6	95.6	383.2	254.4
	7	110.6	368.3	254.4
	8	125.5	353.4	339.2
	9	140.4	338.5	339.2
	10	155.3	323.6	424.0

Table 12: Voice and data bit rates for G.726 coder and various downstream/upstream data rates, when one line is handling data modem traffic using demod-remod.

G.726 (two data modem lines)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128	1			
	2	0	61.6	0
192 11.42	1			
	2	0	125.6	0
	3	29.8	95.8	84.8
	4	49.1	76.5	84.8
256 11.48 to 13.14	1			
	2	0	189.6	0
	3	29.8	159.8	84.8
	4	49.1	140.5	84.8
	5	65.3	124.3	169.6
	6	80.6	109.0	169.6
320 9.65 to 10.98	1			
	2	0	253.6	0
	3	29.8	223.8	84.8
	4	49.1	204.5	84.4
	5	65.3	188.3	169.6
	6	80.6	173.0	169.6
384 9.21 to 11.42	1			
	2	0	317.6	0
	3	29.8	287.8	84.8
	4	49.1	268.5	84.8
	5	65.3	252.3	169.6
	6	80.6	237.0	169.6
	7	95.6	222.0	254.4
	8	110.6	207.1	254.4
512 8.66 to 11.14	1			
	2	0	445.6	0
	3	29.8	415.8	84.8
	4	49.1	396.5	84.8
	5	65.3	380.3	169.6
	6	80.4	365.0	169.6
	7	95.6	350.0	254.4
	8	110.6	335.1	254.4
	9	125.5	320.2	339.2
	10	140.4	305.3	339.2

Table 13: Voice and data bit rates for G.726 coder and various downstream/upstream data rates, when two lines are handling data modem traffic using demod-remod.

G.726 (one fax line and one data modem line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128	1			
	2	0	78.2	0
192 11.42	1			
	2	0	142.2	0
	3	29.8	112.4	84.4
	4	49.1	93.1	84.8
256 10.31 to 11.97	1			
	2	0	206.2	0
	3	29.8	176.4	84.4
	4	49.1	157.1	84.8
	5	65.3	140.9	169.6
	6	80.6	125.6	169.6
320 9.65 to 10.98	1			
	2	0	270.2	0
	3	29.8	240.4	84.4
	4	49.1	221.1	84.4
	5	65.3	204.9	169.6
	6	80.6	189.6	169.6
384 9.21 to 11.42	1			
	2	0	334.2	0
	3	29.8	304.4	84.8
	4	49.1	285.1	84.8
	5	65.3	268.9	169.6
	6	80.6	253.6	169.6
	7	95.6	238.6	254.4
	8	110.6	223.7	254.4
512 8.66 to 11.14	1			
	2	0	462.2	0
	3	29.8	432.4	84.8
	4	49.1	413.1	84.8
	5	65.3	396.9	169.6
	6	80.4	381.6	169.6
	7	95.6	366.6	254.4
	8	110.6	351.7	254.4
	9	125.5	336.8	339.2
	10	140.4	321.9	339.2

Table 14: Voice and data bit rates for G.726 coder and various downstream/upstream data rates, when one line is being used for fax traffic and one line is being used for data modem traffic, using demod-remod.

G.728 (one fax line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 13.63	1	0	111.4	0
	2	29.8	81.6	84.8
	3	49.1	62.3	84.8
192 11.42 to 13.63	1	0	175.4	0
	2	29.8	145.6	84.8
	3	49.1	126.3	84.8
	4	61.7	113.8	84.8
	5	71.1	104.3	169.6
	6	79.7	95.7	169.6
	7	88.6	86.9	169.6
256 10.31 to 13.63	1	0	239.4	0
	2	29.8	209.6	84.8
	3	49.1	190.3	84.8
	4	61.7	177.8	84.8
	5	71.1	168.3	169.6
	6	79.7	159.7	169.6
	7	88.6	150.9	169.6
	8	97.8	141.6	169.6
	9	107.3	132.1	254.4
	10	116.6	122.8	254.4

Table 15: Voice and data bit rates for G.728 coder and various downstream/upstream data rates, when one line is handling fax traffic using demod-remod.

G.728 (two fax lines)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 13.63	1			
	2	0	94.8	0
	3	29.8	65.0	84.8
192 11.42 to 13.63	1			
	2	0	158.8	0
	3	29.8	129.0	84.8
	4	49.1	109.7	84.8
	5	61.7	97.2	84.8
	6	71.1	87.7	169.6
	7	79.7	79.1	169.6
256 10.31 to 13.63	1			
	2	0	222.8	0
	3	29.8	193.0	84.8
	4	49.1	173.7	84.8
	5	61.7	161.2	84.8
	6	71.1	151.7	169.6
	7	79.7	143.1	169.6
	8	88.6	134.3	169.6
	9	97.8	125.0	169.6
	10	107.3	115.5	254.4

Table 16: Voice and data bit rates for G.728 coder and various downstream/upstream data rates, when two lines are handling fax traffic using demod-remod.

G.728 (one data modem line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 13.63	1	0	94.8	0
	2	29.8	65.0	84.8
	3	49.1	45.7	84.8
192 11.42 to 13.63	1	0	158.8	0
	2	29.8	129.0	84.8
	3	49.1	109.7	84.8
	4	61.7	97.2	84.8
	5	71.1	87.7	169.6
	6	79.7	79.1	169.6
	7	88.6	70.3	169.6
256 10.31 to 13.63	1	0	222.8	0
	2	29.8	193.0	84.8
	3	49.1	173.7	84.8
	4	61.7	161.2	84.8
	5	71.1	151.6	169.6
	6	79.7	143.1	169.6
	7	88.6	134.3	169.6
	8	97.8	125.0	169.6
	9	107.3	115.5	254.4
	10	116.6	106.2	254.4

Table 17: Voice and data bit rates for G.728 coder and various downstream/upstream data rates, when one line is handling data modem traffic using demod-remod.

G.728 (two data modem lines)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 13.63	1			
	2	0	61.6	0
	3	29.8	31.8	84.8
192 11.42 to 13.63	1			
	2	0	125.6	0
	3	29.8	95.8	84.8
	4	49.1	76.5	84.8
	5	61.7	64.0	84.8
	6	71.1	54.6	169.6
	7	79.7	45.9	169.6
256 10.31 to 13.63	1			
	2	0	189.6	0
	3	29.8	159.8	84.8
	4	49.1	140.5	84.8
	5	61.7	128.0	84.8
	6	71.1	118.6	169.6
	7	79.7	109.9	169.6
	8	88.6	101.1	169.6
	9	97.8	91.8	169.6
	10	107.3	82.3	254.4

Table 18: Voice and data bit rates for G.728 coder and various downstream/upstream data rates, when two lines are handling data modem traffic using demod-remod.

G.728 (one fax line and one data modem line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 13.63	1			
	2	0	78.2	0
	3	29.8	48.4	84.8
192 11.42 to 13.63	1			
	2	0	142.2	0
	3	29.8	112.4	84.8
	4	49.1	93.1	84.8
	5	61.7	80.6	84.8
	6	71.1	71.2	169.6
	7	79.7	62.5	169.6
256 10.31 to 13.63	1			
	2	0	206.2	0
	3	29.8	176.4	84.8
	4	49.1	157.1	84.8
	5	61.7	144.6	84.8
	6	71.1	135.2	169.6
	7	79.7	126.5	169.6
	8	88.6	117.7	169.6
	9	97.8	108.4	169.6
	10	107.3	98.9	254.4

Table 19: Voice and data bit rates for G.728 coder and various downstream/upstream data rates, when one line is being used for fax traffic and one line is being used for data modem traffic, using demod-remod.

G.729 (one fax line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 28.63 to 35.25	1	0	111.4	0
	2	14.9	96.5	42.4
	3	24.6	86.9	42.4
	4	30.8	80.6	42.4
	5	35.5	75.9	84.8
	6	39.9	71.6	84.8
	7	44.3	67.1	84.8
	8	48.9	62.5	84.8
	9	53.6	57.8	127.2
	10	58.3	53.1	127.2

Table 20: Voice and data bit rates for G.729 coder and various downstream/upstream data rates, when one line is handling fax traffic using demod-remod.

G.729 (two fax lines)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 28.63 to 35.25	1			
	2	0	94.8	0
	3	14.9	79.9	42.4
	4	24.6	70.3	42.4
	5	30.8	64.0	42.4
	6	35.5	59.3	84.8
	7	39.9	55.0	84.8
	8	44.3	50.5	84.8
	9	48.9	45.9	84.8
	10	53.6	41.3	127.2

Table 21: Voice and data bit rates for G.729 coder and various downstream/upstream data rates, when two lines are handling fax traffic using demod-remod.

G.729 (one data modem line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 28.63 to 35.25	1	0	94.8	0
	2	14.9	79.9	42.4
	3	24.6	70.3	42.4
	4	30.8	64.0	42.4
	5	35.5	59.3	84.8
	6	39.9	55.0	84.8
	7	44.3	50.5	84.8
	8	48.9	45.9	84.8
	9	53.6	41.2	127.2
	10	58.3	36.5	127.2

Table 22: Voice and data bit rates for G.729 coder and various downstream/upstream data rates, when one line is handling data modem traffic using demod-remod.

G.729 (two data modem lines)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 28.63 to 35.25	1			
	2	0	61.6	0
	3	14.9	46.7	42.4
	4	24.6	37.1	42.4
	5	30.8	30.8	42.4
	6	35.5	26.1	84.8
	7	39.9	21.8	84.8
	8	44.3	17.4	84.8
	9	48.9	12.7	84.8
	10	53.6	8.0	127.2

Table 23: Voice and data bit rates for G.729 coder and various downstream/upstream data rates, when two lines are handling data modem traffic using demod-remod.

G.729 (one fax line and one data modem line)

Upstream bit rate (Kbps)/ Delay (ms)	Voice circuits, including fax/data modem lines	Average voice bandwidth (Kbps), excluding fax/data modem lines	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps), excluding fax/data modem lines
128 28.63 to 35.25	1			
	2	0	78.2	0
	3	14.9	63.3	42.4
	4	24.6	53.7	42.4
	5	30.8	47.4	42.4
	6	35.5	42.7	84.8
	7	39.9	38.4	84.8
	8	44.3	33.9	84.8
	9	48.9	29.3	84.8
	10	53.6	24.6	127.2

Table 24: Voice and data bit rates for G.729 coder and various downstream/upstream data rates, when one line is being used for fax traffic and one line is being used for data modem traffic, using demod-remod.

Calculation of the Standard Deviation

Although calculating the average bandwidth available to data is useful, the average is simply a statement of the long-term availability of bandwidth. Over the short term, the voice activity could be starving the data for bandwidth. If we could calculate the standard deviation of the data bandwidth, we could make a statement about the probability of certain amounts of bandwidth being available for Internet access, even when all the voice circuits are active.

The standard deviation is not a point value, however. If we look at the bandwidth over longer periods of time, it will tend towards the mean. We must calculate the standard deviation over discrete periods of time that are relevant for Internet access. While Internet access times are different for different users, we chose to examine the standard deviation at 1, 3, 5 and 10 second intervals. Given the standard deviation, an analyst can estimate the minimum bandwidth available 95%, 99%, or 99.9% of the time (or any percent desired) during any of these periods.

The standard deviation for data is the same as the standard deviation for voice. Mathematically, if we let D, V, and L represent the bandwidth for Data, Voice, and the Link, then D=L-V. Because L is a constant, the variance of L-V is the same as the variance of V.

The results are presented first. The mathematical model is described afterwards and an example is included. The calculations were all performed in MathCAD.

G.711 Standard Deviation (Kbps)

Lines	1 second	3 seconds	5 seconds	10 seconds
1	48.1	30.3	23.9	17.1
2	47.4	29.7	23.4	16.7
3	48.2	30.2	23.8	17.0
4	51.5	32.3	25.4	18.2
5	55.8	35.0	27.6	19.7
6	60.3	37.9	29.8	21.3

Table 25: Standard deviation for different numbers of voice circuits active for G.711 and different time periods. The standard deviation is the same for the average voice bandwidth and the average data bandwidth.

G.726 Standard Deviation (Kbps)

Lines	1 second	3 seconds	5 seconds	10 seconds
1	24.0	15.1	11.9	8.5
2	23.7	14.8	11.7	8.3
3	24.1	15.1	11.9	8.5
4	25.7	16.1	12.7	9.1
5	27.8	17.5	13.8	9.8
6	30.1	18.9	14.9	10.6
7	32.3	20.3	16.0	11.4
8	34.4	21.6	17.0	12.2
9	36.4	22.9	18.0	12.9
10	38.3	24.1	19.0	13.6

Table 26: Standard deviation for different numbers of voice circuits active for G.726 and different time periods. The standard deviation is the same for the average voice bandwidth and the average data bandwidth. These standard deviations are applicable to the cases of no fax/data modem usage and when fax/data modem traffic is carried via G.711 with 44 octet frames or demod-remod. When used for fax/data modem traffic, the table should be entered with the number of active voice lines, i.e., excluding the lines carrying fax/data modem traffic.

G.728 Standard Deviation (Kbps)

Lines	1 second	3 seconds	5 seconds	10 seconds
1	24.0	15.1	11.9	8.5
2	23.7	14.8	11.7	8.3
3	20.3	12.7	9.9	7.1
4	17.8	11.1	8.7	6.2
5	17.6	10.9	8.6	6.1
6	19.0	11.9	9.3	6.7
7	21.0	13.1	10.3	7.4
8	22.6	14.2	11.1	8.0
9	23.6	14.8	11.6	8.3
10	23.9	15.0	11.8	8.4

Table 27: Standard deviation for different numbers of voice circuits active for G.728 and different time periods. The standard deviation is the same for the average voice bandwidth and the average data bandwidth. These standard deviations are applicable to the cases of no fax/data modem usage and when fax/data modem traffic is carried via G.711 with 44 octet frames or demod-remod. When used for fax/data modem traffic, the table should be entered with the number of active voice lines, i.e., excluding the lines carrying fax/data modem traffic.

G.729 Standard Deviation (Kbps)

Lines	1 second	3 seconds	5 seconds	10 seconds
1	12.0	7.5	5.9	4.2
2	11.8	7.4	5.8	4.2
3	10.1	6.3	5.0	3.5
4	8.9	5.5	4.3	3.1
5	8.8	5.4	4.3	3.1
6	9.5	5.9	4.6	3.3
7	10.5	6.5	5.1	3.7
8	11.3	7.1	5.6	4.0
9	11.9	7.5	5.8	4.1
10	11.9	7.5	5.9	4.2

Table 28: Standard deviation for different numbers of voice circuits active for G.729 and different time periods. The standard deviation is the same for the average voice bandwidth and the average data bandwidth. These standard deviations are applicable to the cases of no fax/data modem usage and when fax/data modem traffic is carried via G.711 with 44 octet frames or demod-remod. When used for fax/data modem traffic, the table should be entered with the number of active voice lines, i.e., excluding the lines carrying fax/data modem trafficc.

Fax/Data modem using 44 octet G.711 frames or Demod/Remod

When communicating fax/data modem traffic with 44 octet G.711 frames or demod/remod, the fax and data modems are assumed to be continuously transmitting. When continuously transmitting, there is no variation in their bandwidth, and hence also no variation in the bandwidth remaining for data. For example, when there are six lines of which two are using fax and/or data modems, the variation in bandwidth is caused by the speaker activity on the remaining four lines, and is exactly the variation calculated for four lines with no fax/data modem operation.

Mathematical Model

We break the time into intervals corresponding to the codec being used (2.5, 5, or 10ms for each interval). Each speaker follows the standard model of talk spurts averaging 352 ms and silent spurts averaging 650 ms, each exponentially distributed. Each line transfers between "talk" and "silent" according to a simple Markov chain, and the codec produces a voice sample for each line that was in talk-state at the beginning of the period. This ignores the mathematical possibility of multiple transitions between talk and silence within a single interval, which we think is a realistic reflection of the physical system.

The total number of lines in talk-state is a Markov chain, easily derived from the Markov chain for an individual line. For example, if there are four lines, the system's Markov model has five states, from zero to four lines in talk-state. There are, for example, two classes of transitions that can change the state from "2-talking" to "3-talking" - either one line goes from silent to talk, or two lines go from silent to talk in the same period that one line goes from talk to silent.

The number of cells generated in an interval is straightforward to calculate from the number of lines in talk-state. Each talk-state line produces a voice sample, then a 3-octet AAL2 mini-header is added to each voice sample, then the AAL2 mini-cells are packed into the 47 octet payload of AAL2 cells, then all complete and partial cells are transmitted every interval. When G.711 is being used for fax and/or data modem, there are some additional octets, and there are also some additional cells within the interval that are transmitted on the 2.5ms boundary of the G.711 coder. For calculation purposes, the numbers of cells transmitted per interval are stored in a Mean Matrix. The rows and columns of the Mean Matrix correspond to the arrival state at the beginning and end of the period. For this one-period matrix the number of cells depends only on the state at the beginning of the period, not the end of the period, so the rows of the matrix are all constant.

We also need a Variance Matrix for the variance of the number of cells generated in a period, conditioned on the beginning and end states. For one period, the conditional number of cells is a constant, so the one step Variance Matrix is all zeroes.

If we have the Transition, Mean, and Variance matrices for "a" steps and for "b" steps, they can be combined to create the Transition, Mean, and Variance matrices for "a+b" steps (see Equations section). Using the matrices for 1 step and the aggregation equations, we can calculate the matrices of 2 steps, then 4, 5, 10, 20, 40, 50, 100, and 200 steps. 200 steps is 1 second for the coders with a 5ms interval.

Equations

Let Ta_{ij} be the "a" step transition matrix - the probability that if you start in state "i" you will be in state "j" after "a" steps. Let Ma_{ij} be the "a" step Mean Matrix - the mean number of cells that will be generated in a period of "a" steps given that you start in state "i" and end in state "j". Let Va_{ij} be the "a" step Variance Matrix - the variance of the number of cells that will be generated in "a" steps given that you start in state "i" and end in state "j".

Let Tb, Mb, and Vb be the corresponding matrices for "b" steps. Then the matrices Tc. Mc, and Vc for c=a+b steps can be calculated as:

$$Tc_{ik} = \sum_j Ta_{ij} Tb_{jk} \qquad (same\ as\ Tc = Ta \times Tb\ in\ matrix\ notation)$$

For the mean, given the path is i-j-k, then the mean number is $Ma_{ij} + Mb_{jk}$. These conditional means can be deconditioned to get the mean:

$$Mc_{ik} = \frac{\sum_j Ta_{ij} Tb_{jk} \left(Ma_{ij} + Mb_{jk}\right)}{Tc_{ik}}$$

For the variance, given the path is i-j-k, then the variance is $Va_{ij} + Vb_{jk}$. Unfortunately, these conditional variances cannot be directly deconditioned. However, the conditional variances and the conditional means can be combined to get the conditional second moments (Second-Moment = Variance + Mean^2). These second moments can be deconditioned to get the second moment, which can then be used with the mean to get the variance:

$$Vc_{ij} = \frac{\sum_j Ta_{ij} Tb_{jk} \left[Va_{ij} + Vb_{jk} + \left(Ma_{ij} + Mb_{jk}\right)^2\right]}{Tc_{ik}} - Mc_{ik}^{\ 2}$$

To get the final mean and variance, we also need the probability of starting in state "i". The conditional terms from the matrices can then be deconditioned.

Numerical Example

Consider G.726 with 4 lines. The transition probabilities for an individual line after a 5 ms period are:

$$\begin{array}{lcl}
\text{Off - to - Off} & e^{-\frac{5}{650}} & = 0.992337 \\
\text{Off - to - On} & 1 - 0.992337 & = 0.007663 \\
\text{On - to - Off} & 0.007663\text{x}\,\dfrac{650}{352} & = 0.014150 \\
\text{On - to - On} & 1 - .014150 & = 0.985850
\end{array}$$

From these, the Transition matrix for the number of active lines is:

$$\begin{bmatrix}
0.969699 & 0.029952 & 3.469321x10^{-4} & 1.785999x10^{-6} & 3.447858x10^{-9} \\
0.013827 & 0.963680 & 0.022320 & 1.723384x10^{-4} & 4.435809x10^{-7} \\
1.971672x10^{-4} & 0.027477 & 0.957487 & 0.0147782 & 5.706849x10^{-5} \\
2.811470x10^{-6} & 5.876564x10^{-4} & 0.040946 & 0.951122 & 7.342092x10^{-3} \\
4.008964x10^{-8} & 1.117236x10^{-5} & 1.167586x10^{-3} & 0.054231 & 0.944590
\end{bmatrix}$$

Speech samples are 20 octets. Adding a 3 octet min-header, one cell is enough for one or two lines, two cells are necessary for three or four lines. Once the start state is known, there is no variation in the number of cells generated in a period. The Mean and Variance matrices are

$$M = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 2 & 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 & 2 \end{bmatrix} \qquad V = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Applying the aggregation formulas to these one-step matrices, we can calculate the matrices for two steps, and then 4, 5, 10, 20, 40, 50, 100, 200, 400, 600 steps. 600 steps is 3 seconds. The resulting matrices are:

$$T_{600} = \begin{bmatrix} 0.177086 & 0.383594 & 0.311596 & 0.112494 & 0.01523 \\ 0.177086 & 0.383594 & 0.311596 & 0.112494 & 0.01523 \\ 0.177085 & 0.383594 & 0.311597 & 0.112494 & 0.01523 \\ 0.177085 & 0.383594 & 0.311597 & 0.112495 & 0.01523 \\ 0.177084 & 0.383593 & 0.311597 & 0.112495 & 0.01523 \end{bmatrix}$$

$$M_{600} = \begin{bmatrix} 497.519 & 527.697 & 544.453 & 571.717 & 590.050 \\ 528.697 & 558.876 & 575.632 & 602.896 & 621.229 \\ 545.453 & 575.632 & 592.387 & 619.651 & 637.984 \\ 573.717 & 603.896 & 620.651 & 647.915 & 666.249 \\ 592.050 & 622.229 & 638.984 & 666.249 & 684.582 \end{bmatrix}$$

$$V_{600} = \begin{bmatrix} 12215.8 & 12028.7 & 12058.7 & 12332.5 & 12260.6 \\ 12028.7 & 11841.7 & 11871.6 & 12145.5 & 12073.6 \\ 12058.7 & 11871.6 & 11901.6 & 12175.4 & 12103.6 \\ 12332.5 & 12145.5 & 12175.4 & 12449.3 & 12377.5 \\ 12260.6 & 12073.6 & 12103.6 & 12377.5 & 12305.6 \end{bmatrix}$$

The initial probability vector is the steady state vector

$$\begin{bmatrix} 0.177085 & 0.383594 & 0.311596 & 0.112494 & 0.015230 \end{bmatrix}$$

The mean number of cells is 570.383 cells. The variance is 13030.5; the standard deviation is 114.064 cells. The conversion from cells per 3 seconds to Kilobits per second is:

$$\frac{570.383\,cells}{3\sec} \times \frac{53\,octets}{cell} \times \frac{8\,bits}{octet} \times \frac{Kilobit}{1000\,bits} = 80.614\,Kbps$$

$$\frac{114.064\,cells}{3\sec} \times \frac{53\,octets}{cell} \times \frac{8\,bits}{octet} \times \frac{Kilobit}{1000\,bits} = 16.121\,Kbps$$

Comments on results (including results in Appendix A)

Using the data from these tables, we can make several observations. G.711 is perhaps not the best choice because it can only support a limited number of voice lines. Two lines requires at least 192 Kbps, while four lines requires at least 320 Kbps. However, G.711 provides the lowest delay, at 6 to 9 ms (for 20 octet frames), and can handle fax and data modem calls without any special techniques. Using 44 octet speech frames for G.711 helps with lower upstream data rates, allowing support of a single voice circuit on an upstream line of 128 Kbps at a slightly higher delay. Other than this, the use of 44 octet frames does not appear to provide any advantage for handling voice circuits. We did find that 44 octet frames were useful for transport of fax/data modem traffic in G.711 form since that traffic is less sensitive to delay.

Beyond G.711, the provider must decide whether the lines will support fax and/or data modem calls and, if so, how these calls will be handled. If the fax/data modem line is to be switched to G.711, we need an upstream data rate of about 192 kbps to be able to support a reasonable number of lines, and then only if we restrict the subscriber to one fax/data modem line. At 192 Kbps, G.726 will provide three lines, and G.728 will provide four. G.729 can provide up to four lines, with one line for fax/modem operation, but the delay is high, at 32 ms. If more than one fax/data modem line is to be provisioned, switching to G.711 for the fax/data modem will probably not be acceptable, except at high upstream bit rates.

Using demod-remod for fax/data modem calls provides a superior solution from a bandwidth point of view but adds complexity in detecting the fax/data modem call. For example, at 128 Kbps with G.728, operation with two fax calls and one voice call still provide an average of about 65 Kbps for data, while G.729 can provide almost 80 Kbps for data.

If fax and/or data modem calls are not supported, a number of speech coders may be chosen. G.726 is a fairly simple coder and supports an adequate number of lines for upstream data rates above 128Kbps. Delay is acceptable at about 9 to 14 ms (15 to 26 ms for 44 octet speech frames). G.726 can handle all of the CLASS functions and will pass all DTMF, MF and call progress tones acceptably.

G.728 provides support for more voice circuits but perhaps not enough to make it compelling compared to G.726 for residential services if fax/data modem operation is not required. Delay is acceptable at 10 to 14 ms. G.729 provides the ability to handle a large number of voice circuits at relatively low upstream bit rates but introduces significant delay – approximately 29 to 35 ms. It also requires special processing to handle CLASS functions, DTMF, MF and call progress tones acceptably.

When the requirement to handle up to two fax/data modem calls is included, our selection of coders is more limited. Considering only the “demod-remod” technique, G.728 will provide support for only three lines at the lowest upstream line rate considered (128 Kbps), with a one-way delay of 14 ms. G.729 supports many more lines but introduces a large amount of delay, about 29 ms when supporting three voice circuits.

For lines with limited upstream data rates (rates of 128 Kbps and below), the optimum solution may be to utilize G.728 when a smaller number of lines are in use, and dynamically switch to G.729 when more than a critical number is active (the critical number is 3 for 128 Kbps lines). For line rates of 192 Kbps and above, the optimum solution may be to use G.728 for all cases.

Bibliography

[BRA69] Brady, Paul T., A model for generating on-off speech pattern in two-way conversation. *The Bell System Technical Journal*, Vol 48, pp 2445-2472, Sep 1969.

[HEN00] Henderson, P. Michael and William Lipp. *Eliminating the Last Mile Bottleneck*. January 2000, available at http://members.cox.net/michael.henderson/

Appendix A

The 20 octet frame size used for G.711 and G.726 in the main part of this paper is not optimal for line capacity, especially at upstream line rates of 128 Kbps. A 44 octet frame size can be carried in a single AAL2 cell, providing greater bandwidth efficiency at the cost of delay. The following two tables provide the line capacity for G.711 and G.726 with 44 octet frame sizes, at different upstream data rates.

G.711

Downstream/ upstream bit rate (Kbps) - Upstream delay (ms) – Round trip delay (ms)	Voice circuits	Average voice bandwidth (Kbps)	Average downstream data bandwidth (Kbps)	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps)
384/128 14.31 23.83	1	27.1	356.9	100.9	77.1
512/192 12.81 to 14.13 21.07 to 24.11	1	27.1	484.9	164.9	77.1
	2	54.2	457.8	137.8	154.2
768/256 10.81 to 14.13 19.42 to 23.83	1	27.1	740.9	228.9	77.1
	2	54.2	713.8	201.8	154.2
	3	81.2	686.8	174.8	231.3
1,024/320 10.15 to 14.13 18.48 to 23.70	1	27.1	996.9	292.9	77.1
	2	54.2	969.8	265.8	154.2
	3	81.2	942.8	238.8	231.3
	4	108.3	915.7	211.7	308.4
1,024/384 9.71 to 13.02 18.04 to 22.59	1	27.1	996.9	356.9	77.1
	2	54.2	969.8	329.8	154.2
	3	81.2	942.8	302.8	231.3
	4	108.3	915.7	275.7	308.4
1,544/512 9.16 to 13.30 17.21 to 22.72	1	27.1	1,516.9	484.9	77.1
	2	54.2	1,489.8	457.8	154.2
	3	81.2	1,462.8	430.8	231.3
	4	108.3	1,435.7	403.7	308.4
	5	135.4	1,408.6	376.6	385.5
	6	162.5	1,381.5	349.5	462.5

Table 29: Voice and data bit rates for G.711 coder with 44 octet speech frames and various downstream/upstream data rates.

G.726

Downstream/ upstream bit rate (Kbps) - Upstream delay (ms) – Round trip delay (ms)	Voice circuits	Average voice bandwidth (Kbps)	Average downstream data bandwidth (Kbps)	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps)
384/128 19.63 to 26.25 34.83 to 43.67	1	13.5	370.5	114.5	38.5
	2	27.1	356.9	100.9	77.1
	3	40.6	343.4	87.4	115.6
512/192 17.42 to 24.04 32.07 to 41.18	1	13.5	498.5	178.5	38.5
	2	27.1	484.9	164.9	77.1
	3	40.6	471.4	151.4	115.6
	4	54.2	457.8	137.8	154.2
768/256 16.31 to 24.59 30.42 to 41.46	1	13.5	754.5	242.5	38.5
	2	27.1	740.9	228.9	77.1
	3	40.6	727.4	215.4	115.6
	4	54.2	713.8	201.8	154.2
	5	67.7	700.3	188.3	192.7
	6	81.2	686.8	174.8	231.3
1,024/320 15.65 to 24.93 29.48 to 41.65	1	13.5	1,010.5	306.5	38.5
	2	27.1	996.9	292.9	77.1
	3	40.6	983.4	279.4	115.6
	4	54.2	969.8	265.8	154.2
	5	67.7	956.3	252.3	192.7
	6	81.2	942.8	238.8	231.3
	7	94.8	929.2	225.2	269.8
	8	108.3	915.7	211.7	308.4
1,024/384 15.21 to 24.04 29.04 to 41.18	1	13.5	1,010.5	370.5	38.5
	2	27.1	996.9	356.9	77.1
	3	40.6	983.4	343.4	115.6
	4	54.2	969.8	329.8	154.2
	5	67.7	956.3	316.3	192.7
	6	81.2	942.8	302.8	231.3
	7	94.8	929.2	289.2	269.8
	8	108.3	915.7	275.7	308.4
	9	121.9	902.1	262.1	346.9

G.726 (continued)

Downstream/ upstream bit rate (Kbps) - Upstream delay (ms) – Round trip delay (ms)	Voice circuits	Average voice bandwidth (Kbps)	Average downstream data bandwidth (Kbps)	Average upstream data bandwidth (Kbps)	Peak voice bandwidth (Kbps)
1,544/512 14.66 to 22.11 28.21 to 38.13	1	13.5	1,530.5	498.5	38.5
	2	27.1	1,516.9	484.9	77.1
	3	40.6	1,503.4	471.4	115.6
	4	54.2	1,489.8	457.8	154.2
	5	67.7	1,476.3	444.3	192.7
	6	81.2	1,462.8	430.8	231.3
	7	94.8	1,449.2	417.2	269.8
	8	108.3	1,435.7	403.7	308.4
	9	121.9	1,422.1	390.1	346.9
	10	135.4	1,408.6	376.6	385.5

Table 30: Voice and data bit rates for G.726 coder with 44 octet speech frames and various downstream/upstream data rates.