Eliminating the Last Mile Bottleneck

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Agenda

- Technology and Market Drivers
- Performance Requirements
- VoDSL System Architecture
- Closed Form Analysis
- Non-Closed Form Analysis
- Issues and Caveats
- Summary

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Technology and Market Drivers

- **Backbone bandwidth growing rapidly.**
- **But… access bandwidth limited by copper capacity.**
  - It will be decades before the local loop converts to fiber.
- **Digital Subscriber Loop (DSL) technology reaching Shannon limits.**
  - HDSL2 made significant improvement – T1 and E1 over a single local loop.
  - Other techniques must be found to increase loop capacity.
- **Large providers will offer a bundle of services.**
  - Especially voice and Internet access.
  - Also, long distance, cellular service, paging, and entertainment.

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Solution

- **Offer voice and data access over the same local loop.**
- **Voice and data mix well.**
  - Voice is sparsely used but must have low delay.
  - Data can tolerate delay.
- **Use of speech coders and silence detection can increase capacity of the line.**
  - And speech coders use signal processing which is declining in cost.
- **Question explored in this presentation is "What is the capacity of a line?"**

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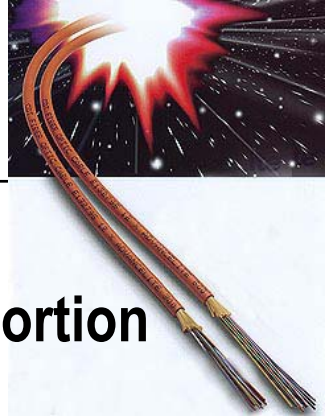
Performance Requirements



- **For voice, the maximum one-way delay over the DSL portion of the link must not exceed 20 ms.**
  - And even then, echo cancellers must be implemented.
- **The maximum queueing delay in the system must not exceed 10 ms, 99% of the time, under worst case load.**
- **It must be possible to reserve bandwidth for data.**
  - To avoid “starving” the computer users under worst case voice loads.
- **It must be possible to use the voice lines for fax and/or modem traffic.**

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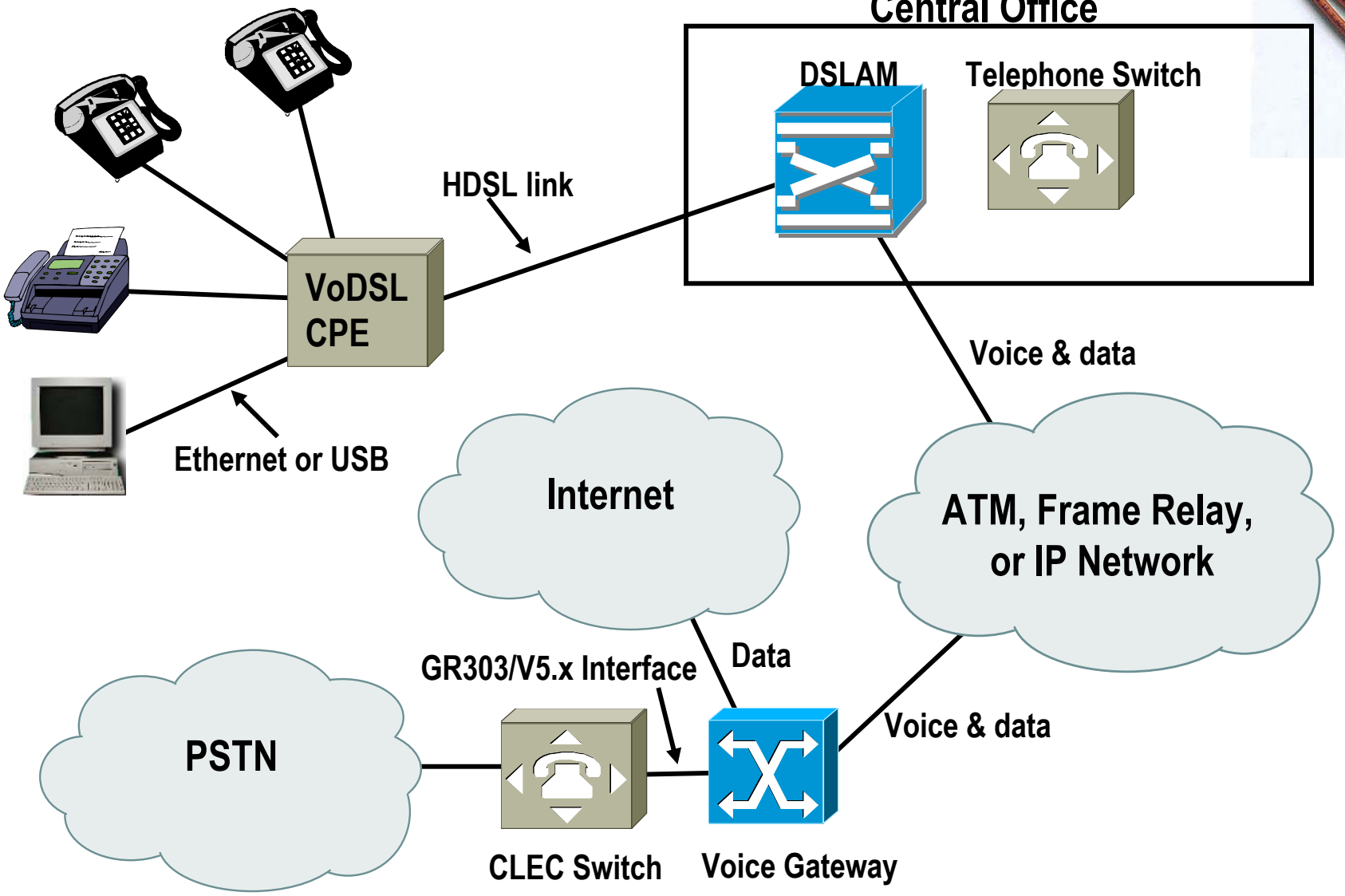
VoDSL System Configuration



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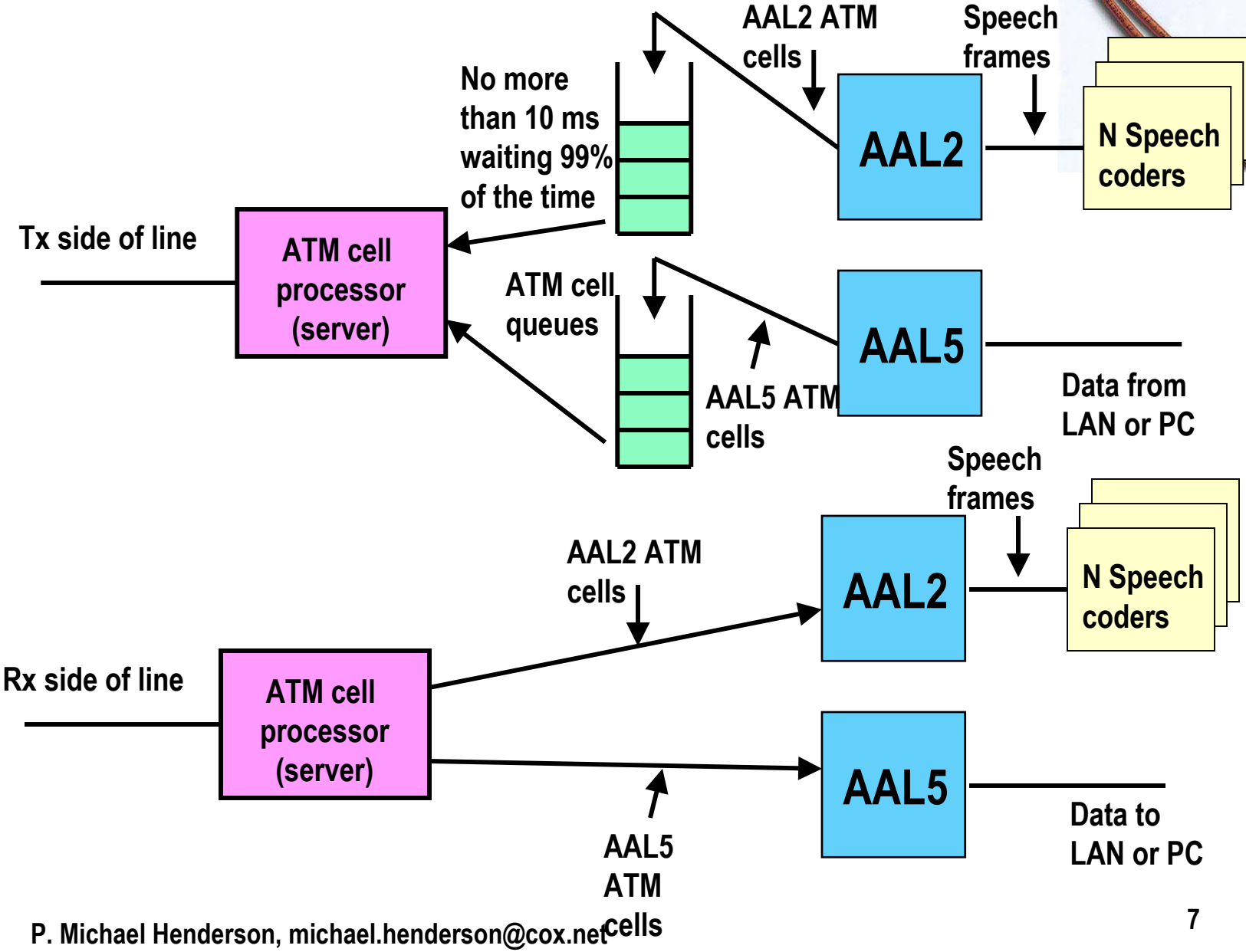
VoDSL Queueing Model



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Closed Form Analysis

- M/M/1 queue discipline assumed.
- ATM assumed for the low level protocol, with voice carried over AAL2 and data over AAL5.
- G.711, G.726 (32Kbps), G.728 and G.729 analyzed.
  - 20 octet frames used for G.711 and G.726.
  - 10 octet frames used for G.729 and G.729
- 35% voice activity assumed (353/(352+650)).
- Guaranteed data bandwidths of 64, 128, 192, 256, 384 and 512Kbps analyzed.
- HDSL line rate of 768Kbps used in all cases.
- System configured such that, with all voice lines active, 99% of the time, the queueing delay will be less than 10 ms.

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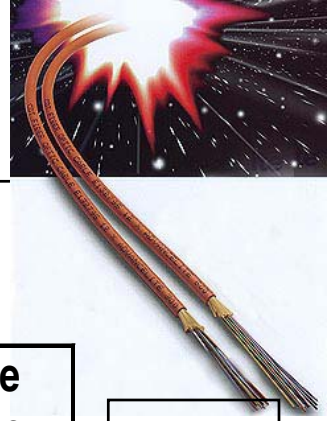
System Capacity Using G.711



Guaranteed data rate (Kbps)	Number of voice ports	Average queueing system delay (ms)	99% system delay (ms)	Average data rate (Kbps)
64	18	2.34	8.73	245.1
128	16	2.42	8.94	303.2
192	14	2.50	9.20	361.3
256	12	2.59	8.70	419.4
384	8	2.80	9.39	535.6
512	4	3.03	7.45	651.8

Half an E1 of voice

- Inherently provides ability to support fax and modems.
- Worst case queueing delay is 13.5 ms (2.5 ms to buffer the voice, 10 ms queueing delay, and 1 ms transmission time).

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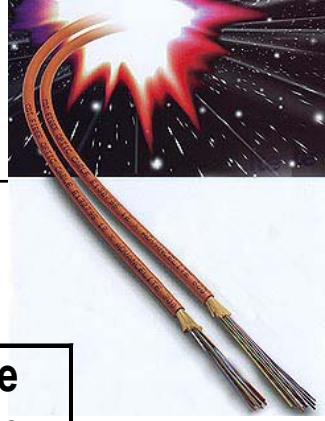
System Capacity Using G.726 (32Kbps)



Guaranteed data rate (Kbps)	Number of voice ports	Average queueing system delay (ms)	99% system delay (ms)	Average data rate (Kbps)
64	37	2.54	9.94	230.6
128	33	2.64	9.61	288.7
192	29	2.74	9.94	346.8
256	24	2.59	8.70	419.4
384	16	2.80	9.39	535.6
512	9	3.38	9.11	637.3

One E1 of voice

One T1 of voice

- Good tradeoff between delay and number of voice lines supported.
- Worst case queueing delay is 16 ms (5 ms to buffer the voice, 10 ms queueing delay, and 1 ms transmission time).

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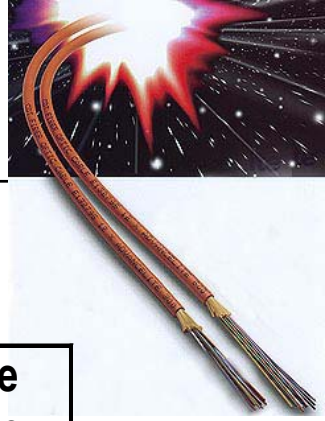
System Capacity Using G.728



Guaranteed data rate (Kbps)	Number of voice ports	Average queueing system delay (ms)	99% system delay (ms)	Average data rate (Kbps)
64	66	2.61	9.94	226.2
128	58	2.59	9.61	291.9
192	51	2.70	9.94	349.3
256	43	2.67	9.52	415.0
384	29	2.91	9.39	529.9
512	16	3.40	9.11	636.7

Two T1's of voice

One T1 of voice

- Better tradeoff between delay and number of voice lines supported.
- Worst case queueing delay is 17 ms (5 ms coder delay, 10 ms queueing delay, 1 ms transmission time, and 1 ms for decoding).

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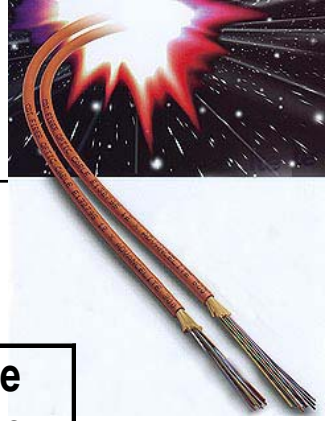
System Capacity Using G.729



Guaranteed data rate (Kbps)	Number of voice ports	Average queueing system delay (ms)	99% system delay (ms)	Average data rate (Kbps)
64	132	2.61	9.94	226.2
128	116	2.59	9.61	291.9
192	103	2.77	9.84	345.2
256	87	2.74	9.52	410.9
384	59	2.99	9.39	525.8
512	32	3.40	9.11	636.7

~Four E1's of voice

~Two E1's of voice

- Excessive delay but largest number of voice lines.
- Worst case queueing delay is 31 ms (15 ms coder delay, 10 ms queueing delay, 1 ms transmission time, and 5 ms for decoding).

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Non-Closed Form Analysis

- **Simulation using MathCAD.**
- **Various line rates examined, from 384 Kbps to 1.544 Mbps.**
- **Only one coder, G.728, examined.**
  - Relatively low bit rate, high quality speech, and acceptable delay characteristics.
- **Attempt to more accurately model real world.**
  - Embedded Markov chain to model persistence of speech.
  - Jitter model to account for (1) speech frames carried in two ATM AAL2 cells, and (2) AAL5 data cells transmitted between AAL2 voice cells.

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System Capacity – 384 and 512 Kbps line

Line rate (Kbps)	Guaranteed data rate (Kbps)	Voice Speed (Kbps)	Number of voice ports	Average data rate (Kbps)
384	64	320	24	186
	128	256	18	235
	192	192	12	283
512	64	448	36	215
	128	384	30	2565
	192	320	24	314
	256	256	18	363

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System Capacity – 768 and 1024 Kbps line

Line rate (Kbps)	Guaranteed data rate (Kbps)	Voice Speed (Kbps)	Number of voice ports	Average data rate (Kbps)
768	64	704	63	249
	128	640	56	307
	192	576	50	356
	256	512	43	414
	384	384	30	521
	512	256	18	619
1024	64	960	91	274
	128	896	84	332
	192	832	77	390
	256	768	70	447
	384	640	56	563
	512	512	43	670
	768	256	18	875

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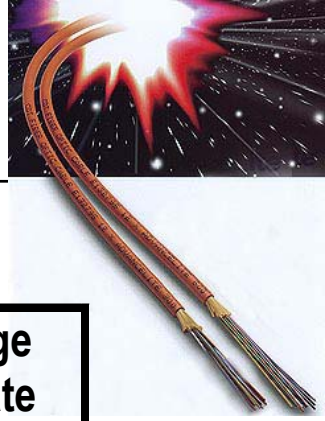
System Capacity – 1544 Kbps line



Line rate (Kbps)	Guaranteed data rate (Kbps)	Voice Speed (Kbps)	Number of voice ports	Average data rate (Kbps)
1544	64	1480	148	325
	128	1416	141	382
	192	1352	134	440
	256	1288	127	498
	384	1160	113	613
	512	1032	99	729
	768	776	71	959
	1000	544	46	1165
	1024	520	44	1181

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Standard Deviation of Data Bandwidth

Voice Lines	Standard Deviation in Kbps			
	1 Second	3 Seconds	5 Seconds	10 Seconds
12	23	15	11	8
24	33	21	16	12
36	40	25	20	14
50	47	30	23	17
63	53	33	26	19
74	57	36	28	20
84	61	38	30	22
99	66	42	33	23

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Handling Fax Traffic

- **G.728 cannot transport analog fax modulation.**
- **However, fax calling and answer tones can be detected and the call handled in a special fashion.**
  - Can switch to 64 Kbps G.711 for that call but reduces capacity.
  - Alternately, can perform “demod-remod” to maximize capacity.
- **Modeled fax calls as constant stream of bits, at 9600 or 14400 bps.**
  - Newer fax machines utilize error control mode (ECM) which causes data to be broken into packets.
  - But older machines simply sent bits in a continuous stream.
  - Assumed old fax machines for worst case analysis.
- **Used 40 octet PDUs with 8 octets of control – one PDU per AAL5 cell (again, worst case).**

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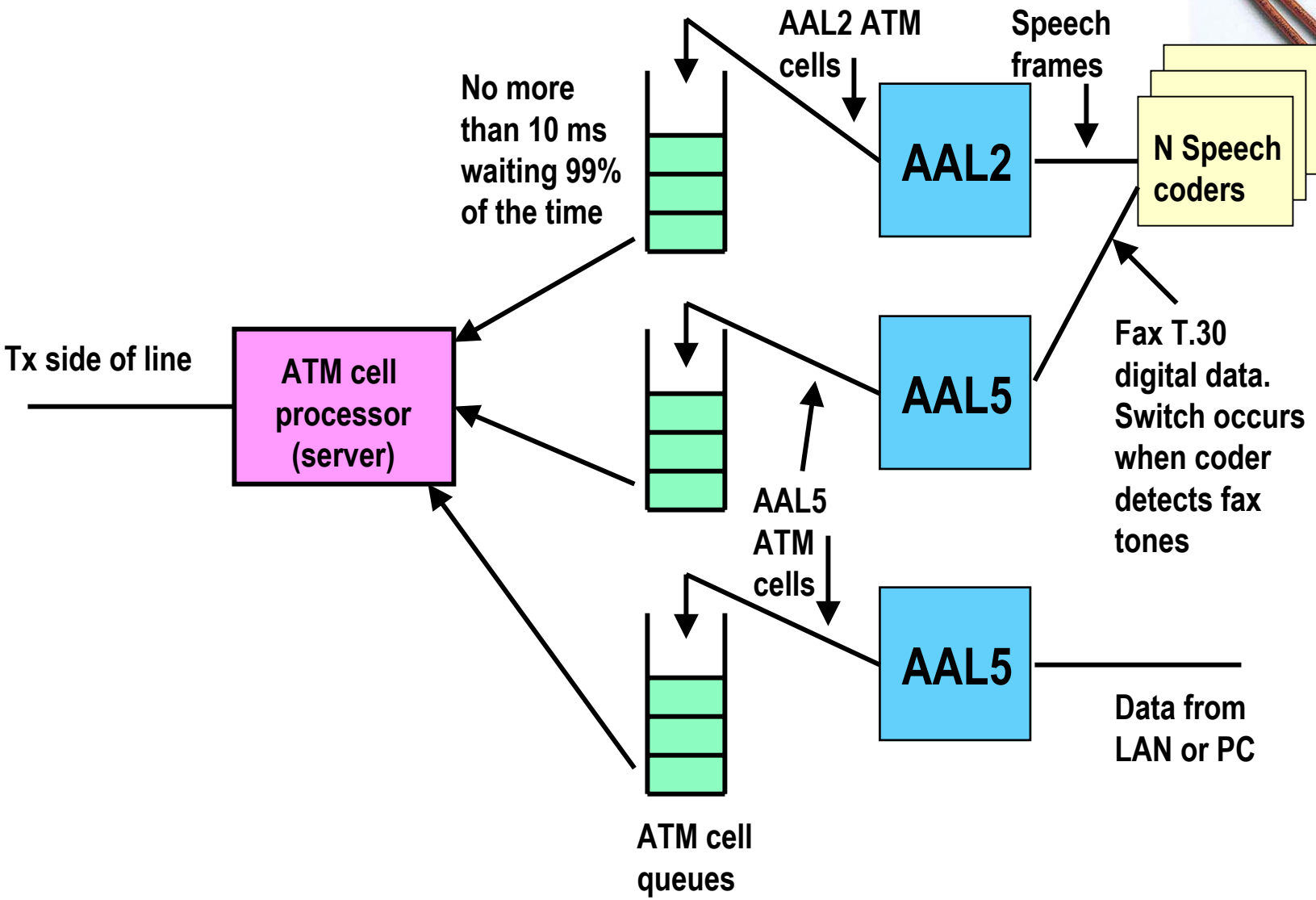
Queueing Model with Fax Traffic



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System Capacity with Fax Demod-Remod

9600 Kbps fax calls	14.4Kbps fax calls	Voice Speed Kbps (excluding fax calls)	Simultaneous Calls (including fax calls)	Average data rate (Kbps)
1	0	627	56	302
2		615	56	298
3		602	55	301
5		576	55	292
10		513	53	296
0	1	621	55	304
	2	602	56	301
	3	583	53	299
	5	545	51	294
	10	449	46	281

- For a 768Kbps line with 128Kbps reserved for data.
- Without fax calls, the capacity of the line is 56 voice circuits and 307 Kbps of data.

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Issues

- **When a speech coder is used, all in band signaling must be detected and forwarded.**
  - Caller ID and other custom local area signaling services (CLASS) functions.
  - DTMF and MF tones.
  - All call progress tones, such as dial tone, busy and ringing, including foreign call progress tones.
- **G.728 does a good job of passing these signals but some require special handling.**

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Use in the Real World

- **When a small number of lines are supported, the speech activity model may not hold.**
  - Speakers may talk more than 35% of the time and standard deviation may be greater.
- **Analysis done for all voice lines busy.**
  - Usually not true for real world – employees are out sick, on vacation, or in meetings.
  - If voice lines used for trunk, they cannot all be busy for very long in order to avoid blocking.
- **We assumed data bandwidth always fully used.**
  - Traffic is bursty, allowing bandwidth to be used by voice circuits.
- **We assumed non-ECM fax traffic and worse case PDU.**
  - ECM fax would not use the line constantly, freeing bandwidth for voice.

Red indicates reduced capacity. Green indicates increased capacity.

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Summary

- Delivery of voice and data over xDSL is the future.
- Use of voice coders and silence suppression allows many more voice lines to be supported on an xDSL line.
- Fax and data modems can be supported more efficiently through the use of demod-remod.

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