TFI Wireless Performance Factors

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Two Key Drivers for New Generations

- Mobile data traffic is growing much more rapidly than connections
- Greatly improving cost/performance of newer technology

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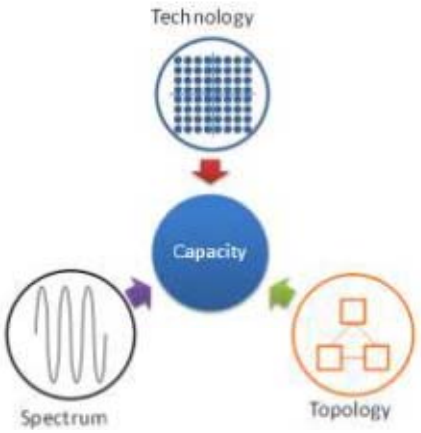
3 Ways to increase wireless Capacity



- Source: Real Wireless

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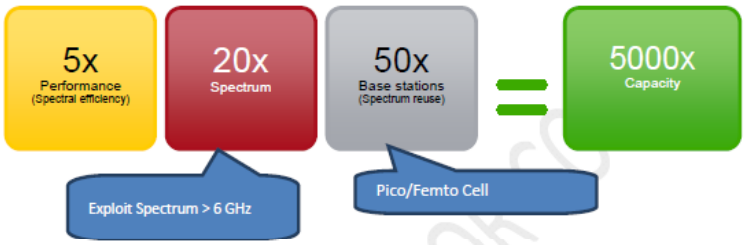
Example: 5G Vs LTE Release 8



- Source: Nokia Siemens Networks

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The three ways are not independent

- You have to have the right technology to add more spectrum across many bands and have it function as a single system.
- You have to have the right technology to minimize inference of many base stations in small cells.
- Some bands of spectrum are better for small cells than others.

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We need to look at more than Bits/s/Hz

- **Spectral efficiency**, **spectrum efficiency** or **bandwidth efficiency** refers to the information rate that can be transmitted over a given bandwidth in a specific communication system.

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Net throughput at the channel or link level is a better measure but not complete

- The **link spectral efficiency** of a digital communication system is measured in *bit*/s/*Hz*, or, less frequently but unambiguously, in *(bit/s)/Hz*. It is the net bitrate (useful information rate excluding error-correcting codes) or maximum throughput divided by the bandwidth in hertz of a communication channel or a data link.

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Performance comparisons should be at the system level

- *system spectral efficiency* or area spectral efficiency is typically measured in *(bit/s)/Hz per unit area*, in *(bit/s)/Hz per cell*, or in *(bit/s)/Hz per site*. **It is a measure of the quantity of users or services that can be simultaneously supported by a limited radio frequency bandwidth in a defined geographic area.**

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Performance comparison notes

- In the past, TFI estimated performance improvements in equivalent voice channels compared to analog 1G = 1. This becomes difficult for systems designed for data.
- We now measure performance improvements by comparing spectral efficiency at the system level.

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Wireless Generations, Performance

Spectral Efficiency of Cellular Wireless Systems

US 1% P Year	Gen	Standard	Max Net Bitrate/ carrier/ Sp stream (Mbits/s)	Bandwidth Per Carrier (MHz)	Max Link Efficiency ((bits/s)/Hz) SISO	MIMO	Typical Reuse	System Efficiency ((bits/s)/Hz/site)
1983	1G	AMPS	0.0003	0.03	0.01		1/7	0.001
1991	2G	D-AMPS	.013 x 3 TS=.039	0.03	1.3		1/9	0.144
2000	2G	GSM	.013 x8 TS =.104	0.2	0.52		1/3	0.173
2000	2G	CDMA 2000	22 calls	1.2288	.0078/call		1	0.172
	2G	**Average**						**0.163**
2002	2.5G	GSM+EDGE	.384 (.2 typ.)	0.2	1.92 (1 typ)		1/3	0.33
2002	2.5G	CDMA 1x PD	0.153	1.2288	0.125		1	0.172
	2.5G	**Average**						**0.251**
2005	3G	CDMA EV-DO	3.072	1.2288	2.5		1	1.3
2005	3G	UMTS	0.384	5	0.077			0.51
	3G	**Average**						**0.905**
2007	**3.5G**	HSDPA	21.1	5	**4.22**		1	**4.22**
2008	4G	LTE	81.6	20	4.08	**16.32**	1	**16.32**
2015	4G	LTE Adv	75	20	3.75	**30**	1	**30**

Source: Technology Futures, Inc.

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Wireless Generations, Performance

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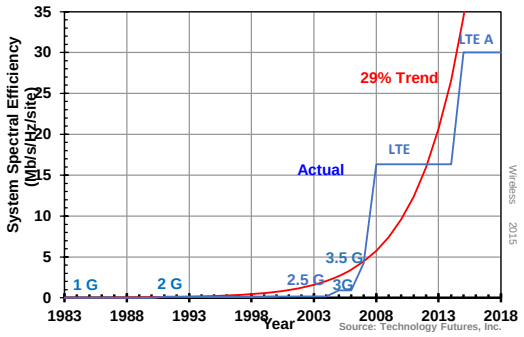

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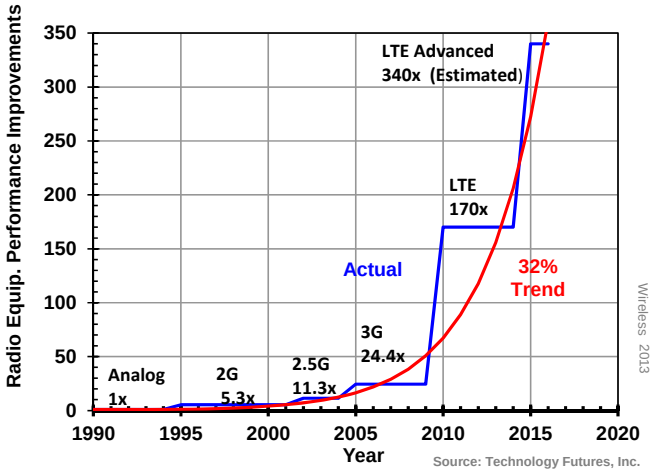
Wireless Generations, Performance (prior method)



Source: Technology Futures, Inc.

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Not much difference in results of the two methods

- The new trend is 29%/year vs 32%/year for the prior.
- The difference is mainly due to the value given 1G as the starting point.
- The new method should work better going forward.

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Issues with performance comparisons

- Improvements to each generation continue thru its life cycle.
- Although 1G and 2G are now history there is still some debate as to how many more voice channels 2G supported. The answer changed over time as 2G improved.
- 2.5G added packet data to a system designed for voice. Improvements and limitations less controversial.

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Issues with performance comparisons (continued)

- 3G was designed for data with obvious advantages over 2.5G for data.
- The issue now is comparing 4G LTE to 3G and improved 3G also referred to as 3.5G and 4G.
- 3G has improved to the point that it is equal to LTE in spectral efficiency but LTE has 4 times the system capacity with 4x4 MIMO.

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Issues with performance comparisons (continued)

- LTE A has eight times the system capacity with 8x8 MIMO.
- Real Wireless did an extensive study of 4G vs. 3G in 2011using system spectral efficiency as the base of comparison. Their findings support TFI's for that point in time.

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