



# Quantum Advances in Wireless

Gain ICs

## QUANTUM ADVANCES

Perhaps the most succinct figure of merit for overall efficiencies in wireless transmission is the ratio of carrier frequency to bitrate. In that regard, an exciting new breakthrough in wireless communication developed by Gain ICs, instantaneous wireless (IW), comes in at 2 cycles/bit with 2 constellations in contrast to the fastest bitrates currently achievable, using Quadrature Amplitude Modulation (QAM) with 256 constellations (IEEE 802.11ac), at 57 cycles/bit and ASK, used in simpler applications that cannot accommodate software demodulation like RFID, comes in at a substantially worse 180,000 cycles/bit. The closer to 1 the better, where IW improves wireless transmission 28 times over QAM and 90,000 times over ASK by this measure. These efficiencies enable quantum advances, significantly improving wireless communication and creating entirely new wireless applications, depicted in Figure 1.

## SALIENT INNOVATION

Quadrature architectures, and in particular 256 quadrature amplitude modulation (QAM), are ubiquitous in contemporary radio frequency (RF) transmissions. They require down conversion to an intermediate frequency (IF) or direct conversion to base frequencies directly (zero IF). In either case, channel noise, like frequency aliasing from down conversion and I/Q synchronization, effectively double noise over Gaussian noise, while also shrinking signal space to increase throughput with higher constellation sizes. Both increased noise and decreased signal space severely degrade transmission, requiring increased power and expense to ameliorate these deficiencies.

Software defined radios (SDR), while attempting to avoid the notorious limitations of quadrature and down conversion, introduce even more impediments to communication in other ways. A huge limitation is the Nyquist sample frequency, sample frequency being at least twice as fast as the inverse of the smallest deviation, effectively pushing carrier to very low frequency. This attenuates range and requires very wide bandwidth to increase bitrates to acceptable levels, albeit still well below those of quadrature modulation. In turn, this spread spectrum solution is hampered by frequency-dependent effects like attenuation and absorption.

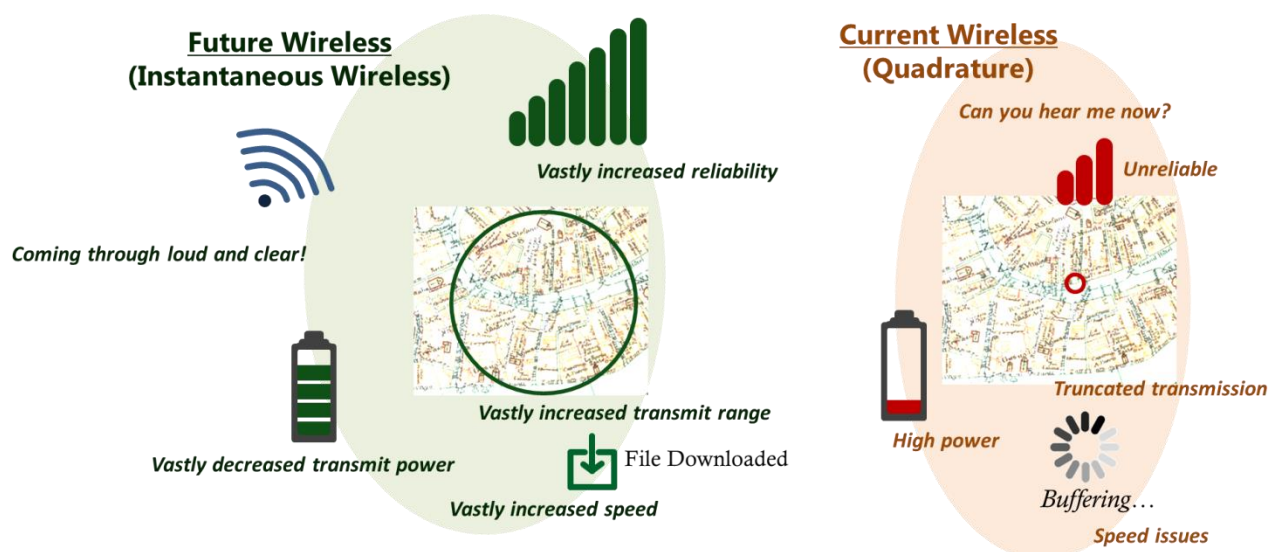


Figure 1. IW improves existing wireless applications and enables entirely new ones, like instantaneous inventory.

The lower SDR carrier frequencies and wider bandwidth also results in another detrimental conflict: the required signal energy needs to be kept low to avoid contention with other signals across wide spectra, while it also needs to be kept high to avoid blackouts. Compromises to such conflicts limit speed, congest frequency spectrum, and lead to less reliability than does quadrature. In contrast, IW eliminates these tradeoffs, optimizing both speed and efficient spectrum utilization.

The ideal modulation of IW allows breakthrough advances over existing standards, as depicted in Figure 2. The limitations of existing methods are eliminated: no down conversion (neither direct or IF) of quadrature and no oversampling issues as with SDR. Reception is simplified to essential operations only: amplify, filter and demodulate. This reduced receiver noise and increased signal space over quadrature solutions and avoidance of sampling limitations like those of SDR allow IW to transmit farther with higher reliability (at essentially zero bit error rate), at higher throughput, with less average bit energy, and with greater link spectral efficiency, surpassing quadrature and SDR in performance.

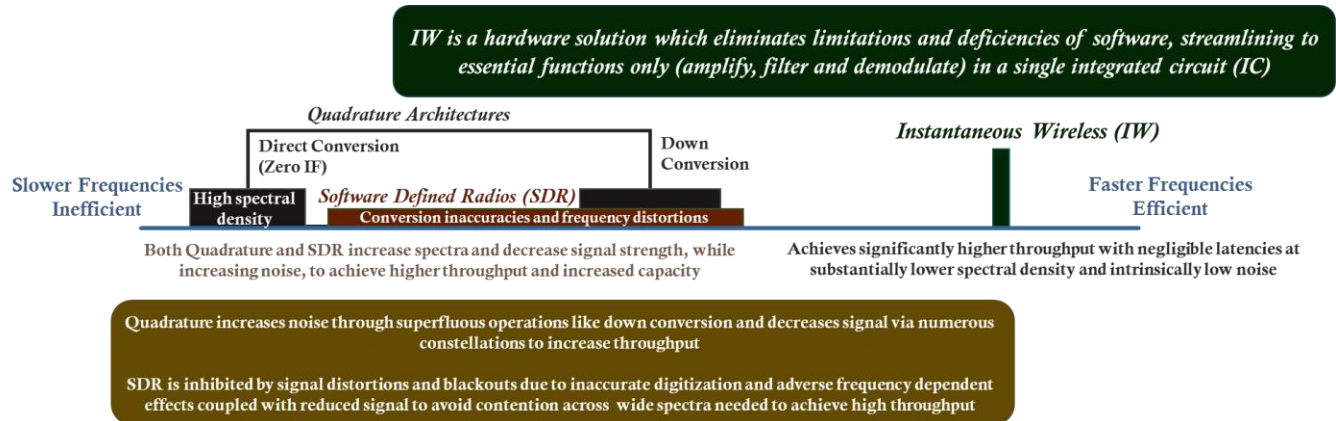


Figure 2. Simplify RF reception to filter, amplify and demodulate only.

## INCREASED RELIABILITY AND RANGE

To cover the range of wireless applications QAM, which is used to achieve the highest throughput at any of the common modulation schemes will be modeled along with Amplitude Shift Keying (ASK), on the other end of application spectrum with low power and small area and thus commonly used in RFID, will also be modeled along with IW.

The same on-die and device noise (1) was used in modeling BER cascade plots for all three, IW, QAM and ASK to ensure most accurate modeling and equivalent comparison. Device parameters define the most dominant device noise at higher frequencies, thermal noise, summed with on-die supply noise for overall Gaussian or white noise. The intrinsic noise floor is the Q function of the square root of 2 times average bit energy times bitrate frequency divided by (1).

$$\sigma_w = 1.373 \sqrt{\frac{kT}{\sqrt{K' \frac{W}{L}} I_D}} + \sigma_{supply} \quad (1)$$

The sensitivity derived from the cascade plots will be overlaid on range plots using Friis transmission equation to establish range for each modulation method. It should be noted that this modeling matches very closely to datasheets for products utilizing both QAM and ASK modulation.

#### Modeling $iW E_b$

Modeling for iW using the standard deviation of noise (1) transposed to phase, and the mean signal, the BER, using the Q function is shown in Figure 3.

$$iW(t) = \sqrt{2E_b f_b} \cos(2\pi(f_c + m_{iW}(\text{trunc}(f_b t))\cos(2\pi f_b t))t)$$

where:

$$m_{iW}(i) = m(i)f_d \quad \text{for } i = 0,1,2...$$

$$f_b \sim \text{modulation frequency, } \frac{f_c}{2}$$

$$f_d \sim \text{modulation amplitude}$$

$$f_c \sim \text{carrier frequency}$$

$$\sigma_{\delta_t} = \frac{\sigma_w}{2\pi(f_c - f_d)\sqrt{2E_b f_b}}$$

$$\mu = f_d$$

$$BER_{iW} = Q\left(\frac{2\pi f_d(f_c - f_d)\sqrt{2E_b f_b}}{1.373 \sqrt{\frac{kT}{K' \frac{W}{L} I_D}} + \frac{\sigma_{supply}}{1.373}}\right)$$

Figure 3. Instantaneous Wireless modeling and BER.

#### Modeling QAM $E_b$

Similarly for QAM, the modeling is in Figure 4.

$$qam_m(t) = \begin{cases} 2\sqrt{\frac{2E_b f_s}{m}} (a_i \cos(2\pi f_c t) - b_i \sin(2\pi f_c t)), & 0 \leq t < \frac{1}{f_s} \\ 0, & \text{otherwise} \end{cases}$$

where:

$$a_i, b_i = \frac{|i|}{i} \left( \frac{\sqrt{m}}{2 \left( \frac{\sqrt{m}}{2} - |i| + 1 \right)} - \frac{1}{2} \right) \quad \text{for } i = \pm 1, \pm 2, \dots, \pm \frac{\sqrt{m}}{2}$$

$$f_s = \frac{f_b}{\log_2 m}$$

$f_c \sim$  carrier frequency

$$\sigma_{\delta_t} = \frac{\sigma_w}{2\pi f_c} \sqrt{\frac{m}{2E_b f_s}} + \sigma_w$$

$$\mu = \frac{1}{\sqrt{m} f_c} + \sqrt{\frac{2E_b f_s}{m}}$$

$$BER_{qam_m} = Q \left( \frac{\frac{1}{f_c} + \sqrt{2E_b f_s}}{2.75\sqrt{m} \left( \sqrt{\frac{kT}{K' \frac{W}{L} I_D}} + \frac{\sigma_{supply}}{1.373} \right) \left( 1 + \frac{1}{\pi f_c} \sqrt{\frac{m}{2E_b f_s}} \right)} \right)$$

Figure 4. BER and modeling for QAM.

Transposing amplitude noise to phase noise, same as was done with IW, yields standard deviation with amplitude component and mean with amplitude component also being source of noise. Apart from signal-space errors increasing proportional to constellation size, QAM channel noise is also very pronounced, like noise aliasing from down convert, carrier recovery phase noise, I/Q phase synchronization, and CW interference are typically double the already pronounced noise from small signal space due to large constellation needed to achieve high bitrates. Channel noise is included as a factor of 2 times device and supply noise per Figure 5.

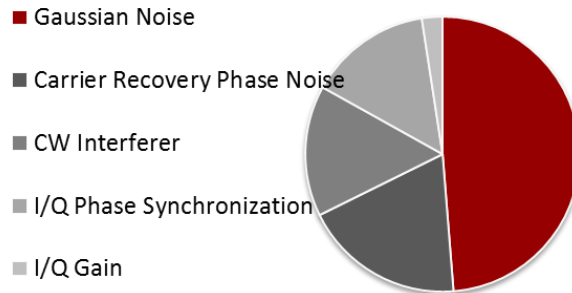


Figure5. QAM channel noise and device and supply noise in red.

### Modeling ASK $E_b$

Similarly modeling for ASK, specifically the version most immune to noise OOK, is in Figure 6.

$$ASK(t) = m_{ask}(trunc(f_b t)) \sqrt{2E_b f_b} \cos(2\pi f_c t)$$

where:

$m_{ask}(i) = m(i)a_d$  (OOK maximum deviation ASK) for  $i = 0,1,2...$

$f_b$  ( $f_s$ ) ~ modulation frequency

$a_d$  ~ modulation amplitude

$f_c$  ~ carrier frequency

$$\sigma_{\delta_t} = \sigma_w$$

$$\mu = a_d \sqrt{2E_b f_b}$$

$$BER_{ask} = Q \left( \frac{a_d \sqrt{2E_b f_b}}{1.373 \sqrt{\frac{kT}{K' \frac{w}{L} I_D}} + \frac{\sigma_{supply}}{1.373}} \right)$$

Figure 6. ASK BER and modeling.

### Range and Reliability

To achieve greater bitrates, conventional RF communication has evolved to 256 QAM, which creates a high number of constellations, counterproductively increasing receiver noise while reducing signal space. The higher QAM throughput comes at the high cost of substantially reduced transmission ranges and degraded BER, translating into increased re-transmissions, which then reduces the overall or effective bitrate, requiring added expense like beamforming to counter such losses.

IW increases the bitrate to greater values than 256 QAM while decreasing constellation size by 128 times to 2 constellations, optimizing signal space while minimizing noise by eliminating down conversion, quadrature demodulation, and amplitude modulation. Thus IW increases reliability and transmit range while achieving highest possible bitrates.

### Spectral Efficiencies

Inherent high throughput and minimal noise of IW result in greater spectral efficiency. Two constellations, versus many required to achieve high throughput in quadrature, and less noise, Gaussian noise only versus pronounced channel noise of quadrature, result in substantially high link spectral efficiency (LSE).

Spectra for three modulation schemes using worst case bit pattern, continuous switching, are calculated using Fourier transform for FSK in (2), IW in (3) and 256 QAM in (4).



$$\sqrt{2E_b f_b} \cos(\pi(2f_c \pm f_b)t) \leftrightarrow \frac{\sqrt{2E_b f_b}}{2} \left[ \frac{\sin 2\pi \left( f_c \pm \frac{f_b}{2} - f \right) \frac{n}{f_b}}{\pi \left( f_c \pm \frac{f_b}{2} - f \right)} \right] + \frac{8E_b \cos^2 \left( \frac{\pi f}{f_b} \right)}{\pi^2 \left( \frac{4f^2}{f_b} - f_b \right)^2} \quad (2)$$

$$\sqrt{2E_b f_b} \cos(2\pi(f_c + m_{iW} \cos(2\pi f_b t))t) \leftrightarrow \frac{\sqrt{E_b f_c}}{4} \left[ \frac{1}{j2\pi(f_c + f_d - f)} + \frac{1}{j2\pi(f_c - f_d - f)} \right] \quad (3)$$

$$\sqrt{2E_b f_s} a_k \cos(2\pi f_c t) - \sqrt{2E_b f_s} b_k \sin(2\pi f_c t) \leftrightarrow \sqrt{\frac{E_b f_s}{2}} (\sqrt{M} + 1) \left[ \frac{\sin \left( 2\pi(\mp f_s + f_c - f) \frac{n}{f_s} \right)}{\pi(\mp f_s + f_c - f)} \right] + \frac{8E_b \cos^2 \left( \frac{\pi f}{f_b} \right)}{\pi^2 \left( \frac{4f^2}{f_b} - f_b \right)^2} \quad (4)$$

Where  $k = 0, \pm 1, \pm 2, \dots \pm (\sqrt{M} + 1)c$

Figure 7 shows this spectra corresponding to average bit energies of frequency shift keying (FSK), 256 QAM and IW. Quadrature average bit energy to overcome much higher noise and larger constellation size, in the case of QAM, necessarily are set at higher per their higher sensitivities, at roughly -40 dBm to -60 dBm. The greater spectral efficiency of IW regardless of modulation magnitude is evident, even at more than double the bitrate. At almost 5 times wider spectra, traditional FSK is considered to be wideband solution.

IW, being 2 clock cycles of carrier clock per bit, inherently high bitrate, spends one of those clock cycles essentially at the carrier frequency and the second clock cycle either faster or slower per modulation. Hence the bulk of the energy focuses at the carrier to reduce width of the occupied bandwidth by orders of magnitude over traditional FSK and still narrowing the width more than 256 QAM.

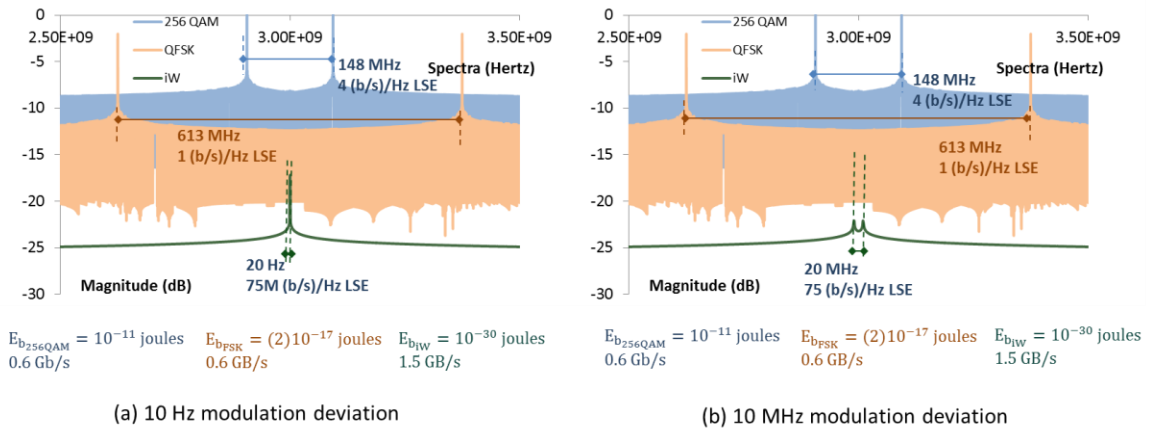


Figure 7. Vast increase in spectral efficiency regardless of modulation amplitude.

## SALIENT ADVANCES

The breakthrough efficiencies of IW allow it to potentially supplant wireless communication across a wide range of applications. Three instances, Fixed wireless, WiFi and item-level tagging, demonstrate such advances in RF communication.

### Fixed Wireless

The receiver sensitivity of IW, using an inherent constellation noise floor, the wide constellation signal space and low noise forming the floor, is at  $10^{-33}$  joules, denoting that sensitivity is not limited architecturally. Realistically, the noise floor is around  $10^{-18}$  joules, thermal noise at higher frequencies, about a 60 dB increase in system gain. If an intrinsic noise floor, supply induced and device noise only as shown in Figure 8, is used, IW receiver sensitivity falls out around  $10^{-11}$  joules, still providing at least a 23 dB increase in system, gain, for 4G, and 13 dB, for 5G. While the 256 QAM modulation used in cellular communication (4G/5G/6G) is orders of magnitude worse than an intrinsic noise floor, owing to large constellation size and notoriously high channel noise, the constellation noise floor of IW is orders of magnitude better than the intrinsic noise floor. While other modulation schemes are architecturally limited in sensitivity, IW is only limited by intrinsic noise.

That 6G potentially has same system gain as IW operating at less expensive 4G conditions emphasizes efficiencies of IW. Thus 6G capacity is achieved at 4G frequency utilizing IW. With a bitrate 15 times faster than 4G and 7 times slower than 6G, IW not only supersedes 4G but supersedes 6G in link spectral efficiency by decreasing spectra, without having to resort to the most integrated and expensive, faster mobility, processes needed to surpass 100 GHz. IW could also operate at 300 GHz, in which case the intrinsic noise floor would lower a 30 dB increase in system gain similar to 4G.

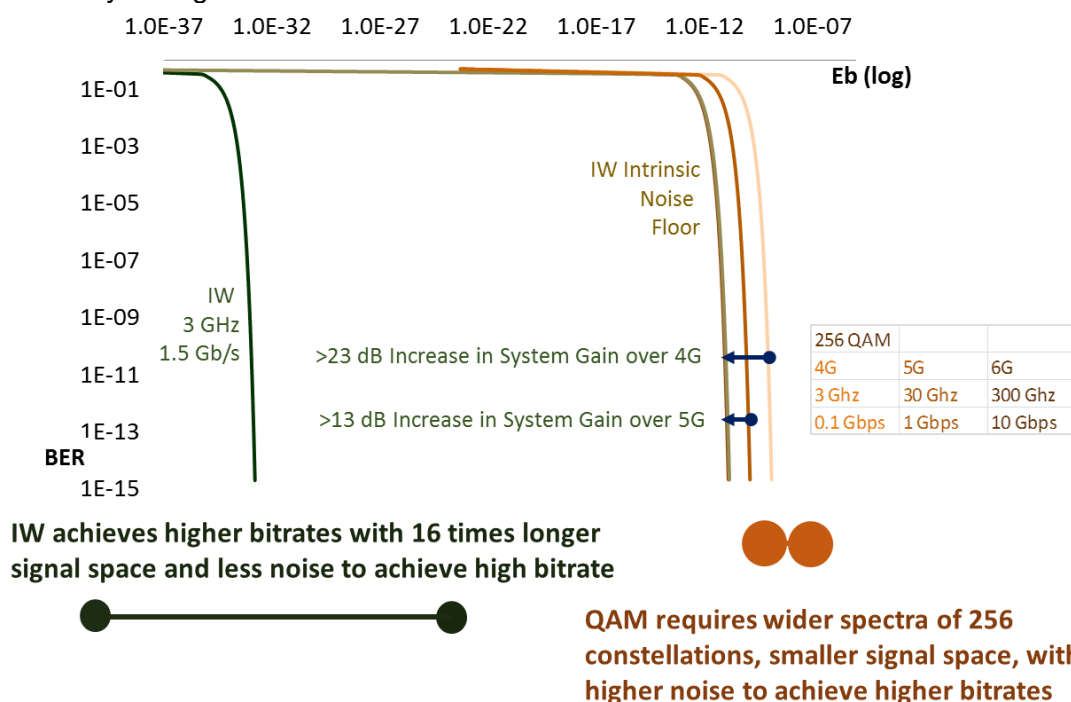


Figure 8. Receiver sensitivity of IW relative to QAM and ASK.



These increases in system gain from IW translate into greater range and reliability. Range, in the minimum, increases with IW by a factor of 10 over the more expensive 6G, in Figure 9. In reality it is expected to increase by more than 100 times, given that the intrinsic noise floor is likely to be much lower, approaching  $10^{-18}$  joules, and with greater innate immunity to noise of phase modulation. Even at  $10^{-15}$  joules, IW exceeds 100 times greater range. Given the isotropic radiation pattern, range is limited by spherical spreading and free-space loss. In practice, increased transmit power, beamforming and phased array antennas, as well as substantially reduced bitrates, are used to extend the range to adequate distances, for QAM especially, partly to compensate for architecturally truncated ranges.

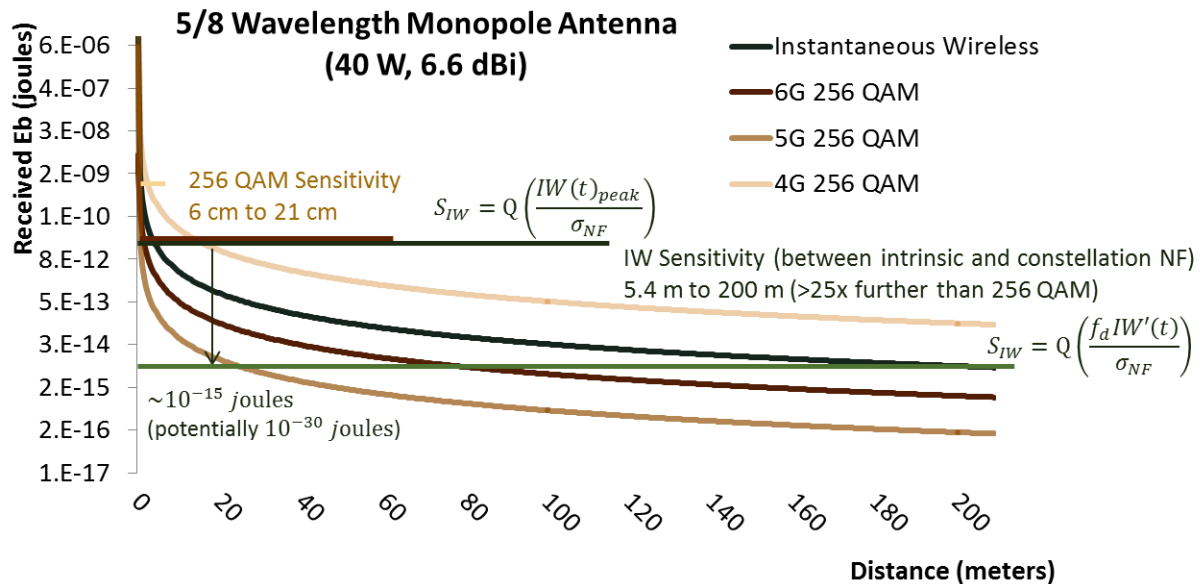


Figure 9. Range and reliability of IW relative to QAM

Decreasing throughput to 5 Mb/s, increasing power, where FCC effective radiated power per channel is limited to 500 W, and implementing simple beamforming, increasing antenna gain by from 2 dB to 5 dB, range can be seen to increase by a factor of more than 60 in Figure 10. When considering the inherent limitation of 2 constellations with smallest noise dots and noise immunity of phase modulation, range likely could reach closer to 2 kilometers. Compared to isotropic case, IW is still more than a 10x improvement in range over 4G QAM. These 32 meters of QAM is still outside of the required 400 meter to 1,600 meter range for LTE mobile, although IW likely would fall into at least the low end, above 400 meters.

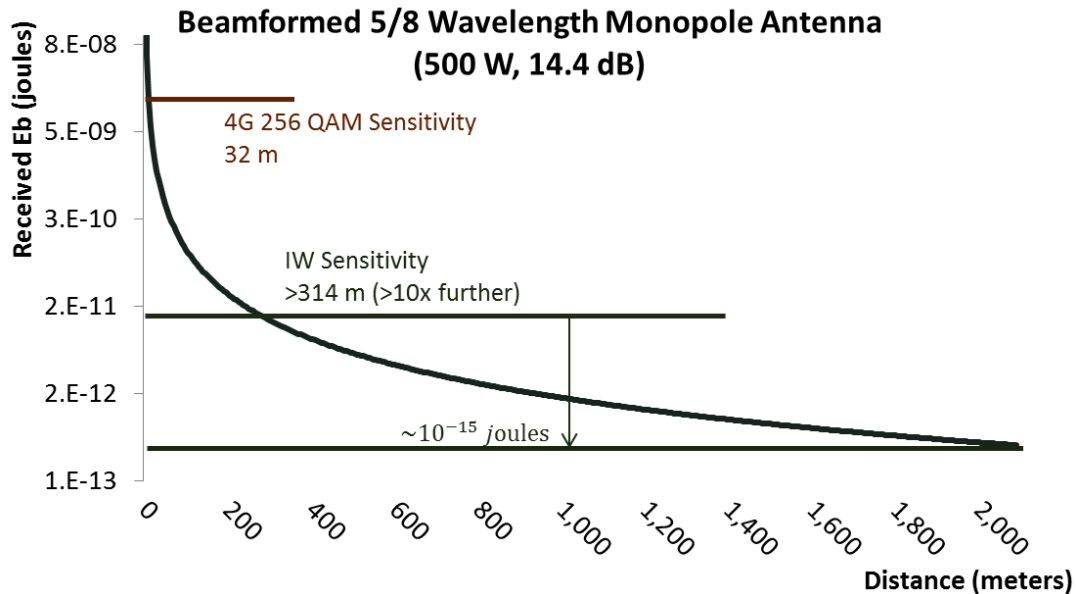


Figure 10. Farther range from increased power, lower throughput and simple beamforming.

Utilizing phased array antennas, as typically done on cellular towers, gain is boosted high enough to achieve the desired longer distances. Using a collinear array with 300 elements demonstrates how 4G falls within the desired range of 400 meters to 1,600 meters, at 736 meters. Under the same conditions IW at least achieves roughly still 10 times increase in range than QAM, placing it well above the highest 1,600 meter limit to 6,640 meters in Figure 11. This is a huge boon to fixed wireless, in particular, over current cellular communications, which advantage would scale with frequency to provide same benefit over 6G.

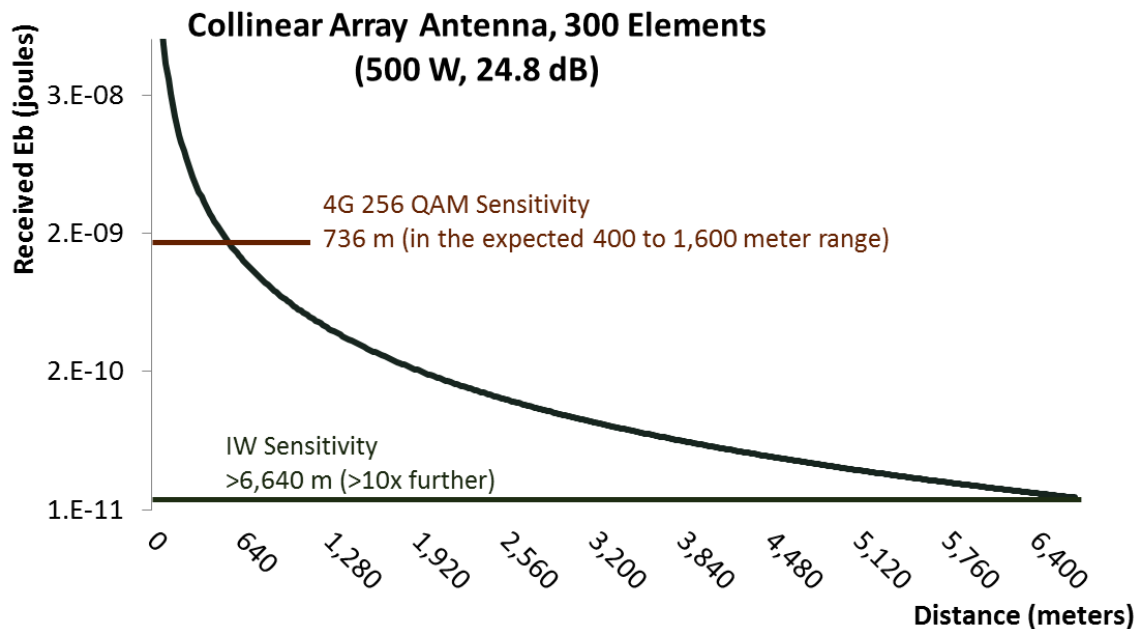


Figure 11. Collinear Arrays on cellular towers increase antenna gain to achieve desired ranges.

With at least 300 joules improvement in receiver sensitivity, IW transmits the same distance as 256 QAM using at least 20 times less power for equal antenna gain and equal transmit frequency. At equal transmit power, IW transmit range will be at least 5 to 10 times farther. These factors of improvement are from limiting IW with worst case noise and could improve substantially given that IW architecture is not the limit to performance as is the case with 256 QAM. An inherently higher noise floor and shrunken signal space to get to higher throughput limit 256 QAM. Transmit range could likely increase to 100 times further than 256 QAM at equal transmit power, or power decrease by greater than a factor of 100 to achieve equivalent range.

While size of an IW radio can be reduced by 90% or more relative to 256 QAM, per 20 times reduction in power, IW transceiver by eliminating down conversion, carrier recovery, and digitization (analog to digital conversion) alone, not to delve into other area increases from 256 QAM complexities, also result in at least a 90% die area reduction in transceiver size, reducing cost proportionally.

### *Interference*

Perhaps the largest impediment to RF communication currently is interference, or desired weak spectral signal being overwhelmed by an adjacent strong signal. While a steeper roll off on filters with tighter accuracy on the front end would help with interference, an indirect solution which offers efficient use of spectra would eliminate interference by moving signals farther apart. In this regard, IW offers an excellent solution to the existing dilemma caused by contention from adjacent signals.

Interference is largely an artifact of a far greater problem, congested and contested spectra caused by the need for increased capacity. Congested spectra is largely due to the large spectral footprint of 256 QAM needed to achieve higher bitrates and is exacerbated by increasing number of channels, hence a lot of big spectral profiles overlapping with smaller profiles.

IW eliminates this pronounced interference by substantially reducing spectral congestion, with spectral profile 7 times smaller and throughput 15 times faster than 256 QAM. Because the IW signal is essentially a fixed-frequency clock with essentially distorted duty cycle from the modulation, spectra is very tight, forming an impulse function in the frequency domain. Throughput, unimpeded by back-end channel noise and truncated signal-space leads to a link spectral efficiency (LSE) roughly 18 times greater than 256 QAM.

This advantage translates into signal separation roughly 18 times farther apart on the spectrum for the same overall capacity, or moving a strong signal 18 times farther away from a target small signal. No more weak signal adjacent to strong signal. Thus IW offers a great solution to the small signal adjacent to large signal dilemma, interference, so common in the ever more congested spectrum.

### *Capacity*

Currently, WiFi grapples with the limitations of QAM, especially from increased noise to achieve needed throughput and the resulting relatively large spectra. The substantially greater LSE of IW eliminates these limitations. Hampering capacity, a key dilemma with WiFi networks, is no



longer an issue. Perhaps in-flight WiFi for entertainment in the industry is best indicative of this. Current efforts pursuing this, albeit expense limits installations to about half of the aircraft only, can accommodate about 22 passengers with WiFi service currently. Calculations with the QAM communications they are using show that only about 18 passengers could watch standard-definition movies simultaneously, allowing 30% more time above communication for multiplexing overhead, as demonstrated in Figure 12. With IW, capacity is no longer an issue and simplicity reduces implication costs to increase feasibility.

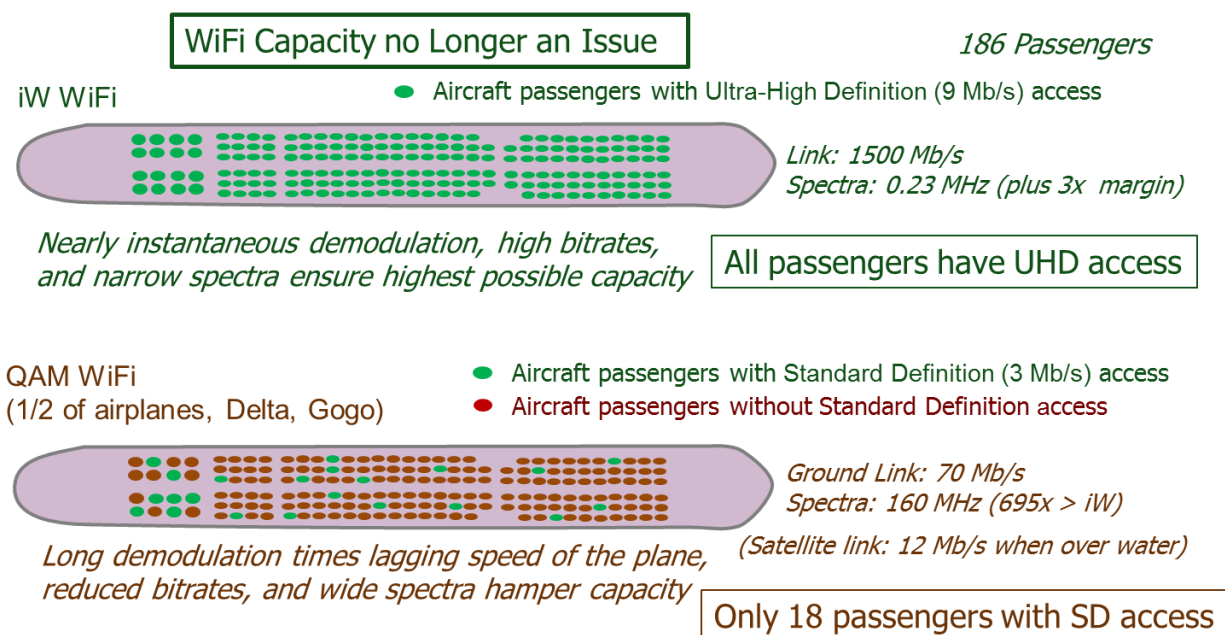


Figure 12. WiFi capacity no longer an issue with IW.

### Item-Level Tagging

Another application where IW advances brings huge performance gains is wireless item-level tagging (ILT), the ubiquitous replacement of barcodes. Radio Frequency Identification (RFID) and Barcodes/QR codes are the two forms of data collection used to process and track items. Although RFID has been around for more than 50 years, a trip to the store reveals that barcodes dominate in the tagging/tracking of most items. Notwithstanding the automated tagging advantage, existing RFID tags do not surpass the performance of barcodes. This is due to the large size-to-sense-range ratio. As antenna size and power increase enough to achieve adequate sense range, ubiquitous use becomes prohibitive. Truncated range, high sense latency, and prohibitive cost are the major limitations of the existing wireless tagging technology.

Current RAID RFID uses amplitude shift keying (ASK) modulation which inhibits ILT. While QAM is inhibited in ILT by software demodulation and large latencies, system gain would be closer to IW in Figure 13. Receiver sensitivity is still orders of magnitude less for IW than both ASK and QAM. Architectural constraints limit receiver sensitivity for QAM and ASK, whereas only intrinsic noise limits the sensitivity of IW, free from architectural constraints.

In Figure 14, Friis transmission equation and sensitivity levels from Figure 13, IW increases transmission range substantially over quadrature transmission and ASK, even when ASK is consuming greater than 200 times high energy. QAM, with higher throughput, is even shorter

range than ASK. Die area and read times are substantially lower for IW than ASK and QAM. This allows IW to compete with barcodes for ILT by keeping die area substantially smaller to rival barcode costs, keeping read range significantly higher than barcodes for automated tracking, and keeping latencies negligible for faster read times.

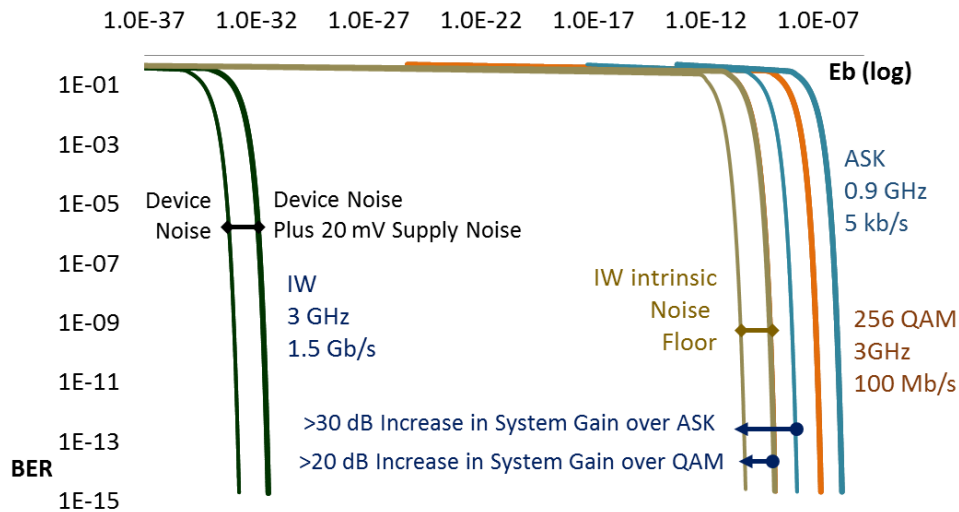


Figure 13. BER, sensitivity, of modulation methods.

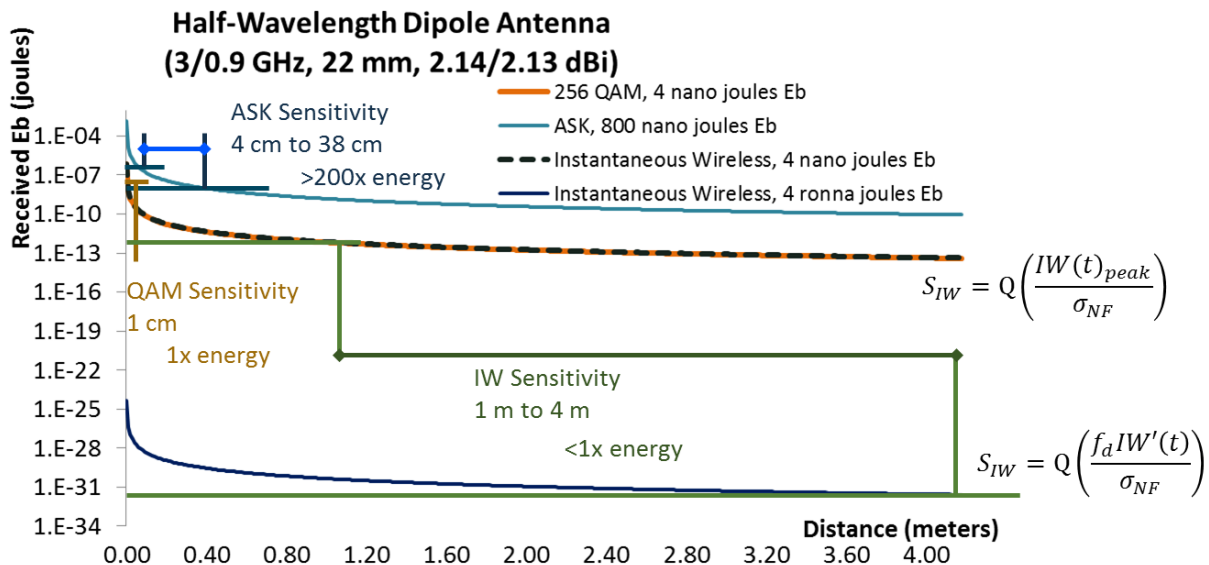


Figure 14. Transmission ranges per sensitivity.

Currently best in class wireless tags, RAIN RFID using ASK modulation, tout sensitivity of -27 dBm and range of 4 centimeters, which matches the modeling of ASK in Figure 13 showing a

sensitivity between -27 dBm and -30 dBm and a transmit range of 4 centimeters to 38 centimeters, depending on induced supply noise. Barcode readers have read ranges about 10 times longer than 4 centimeters. Sense latency for ASK also approaches that of barcodes, in the higher milliseconds, despite automation. Tag costs are about 10 times those associated with barcodes. Thus barcodes remain unchallenged in ubiquitous item tracking. Barcodes, however, require manual orientation besides limited range, adding high substantial costs throughout supply chains via inventory errors and increasing process time, seen in Figure 15.

With barcode sized antenna, Gain ICs' IW tags extend range to above 1 meter, substantially further than existing methods. Die area for an IW tag, the dominant cost when upfront costs are amortized to negligible over high volume, can be kept below barcode costs at \$0.04 per item, the lowest cost from manually scanning a barcode. With millions times faster communication, in the low nanoseconds, IW tagging can now inventory 10,000s of items in mere seconds, millions of times faster than existing RFID. All these advances make IW uniquely positioned as a wireless tagging solution, with the huge advances required to achieve true ILT, to replace barcodes everywhere.

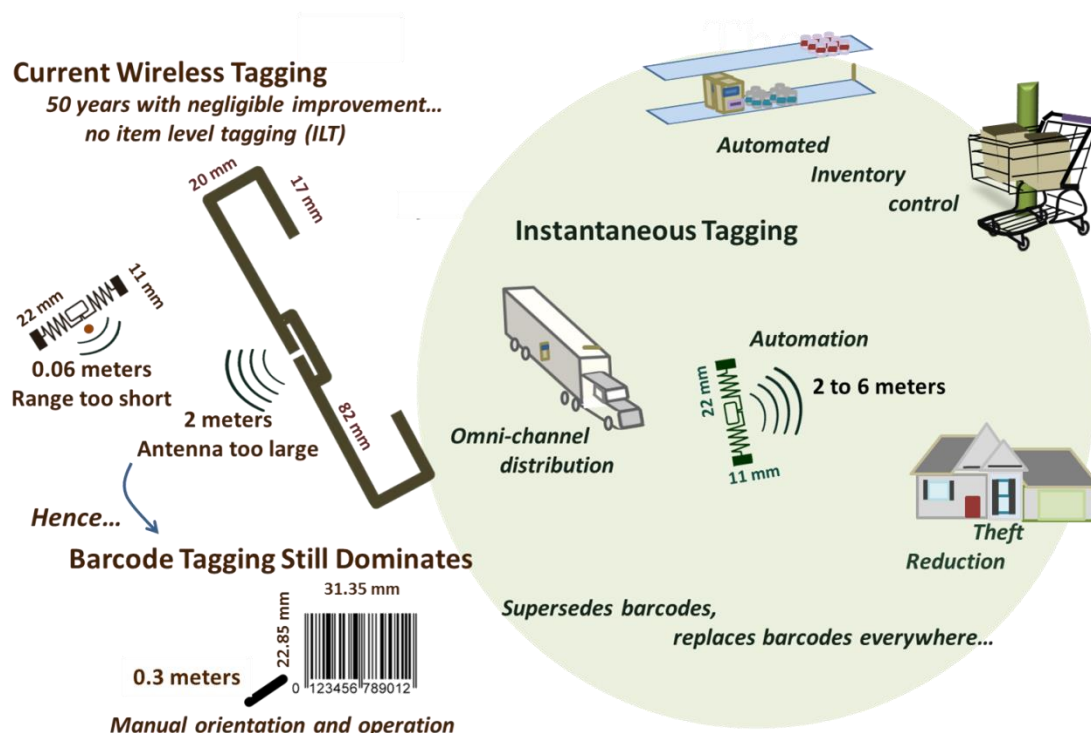


Figure 15. IW ILT far surpasses performance of existing methods.



## INSTANTANEOUS LOOP

The key to achieving IW is instantaneous loops (IL). By eliminating large loop filtering of typical phase locked-loops (PLL), and achieving exact phase tracking with tracking bandwidth to half of the reference frequency, IL achieves phase coherence seen in jitter transfer function and time domain plot of Figure 16.

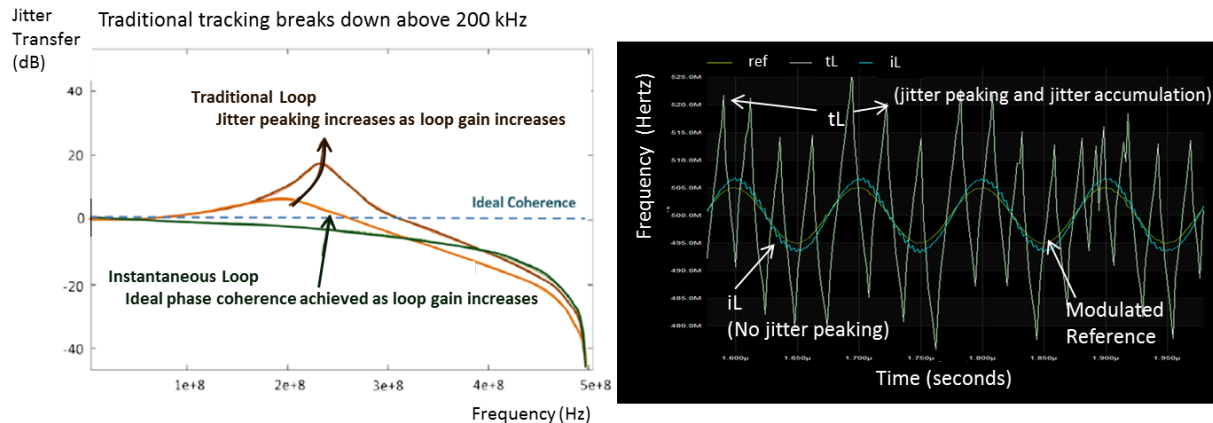


Figure 16. Phase coherence of IL demonstrated as ideal phase tracking.

The high bitrate of IW modulation can be seen in Figure 17, with a modulation amplitude of 10 MHz. The modulation deviation is high to illustrate the stability regardless of swing. In the case of modeling just presented, the modulation amplitude was set to 10 Hz, given the high reliability along with greater range of the low sensitivity. This translates in to link spectral efficiency (LSE) of 75 M(b/s)/Hz, orders of magnitude above any other RF communication link. For instance, 256 QAM typically has LSE around 4 (b/s)/Hz.

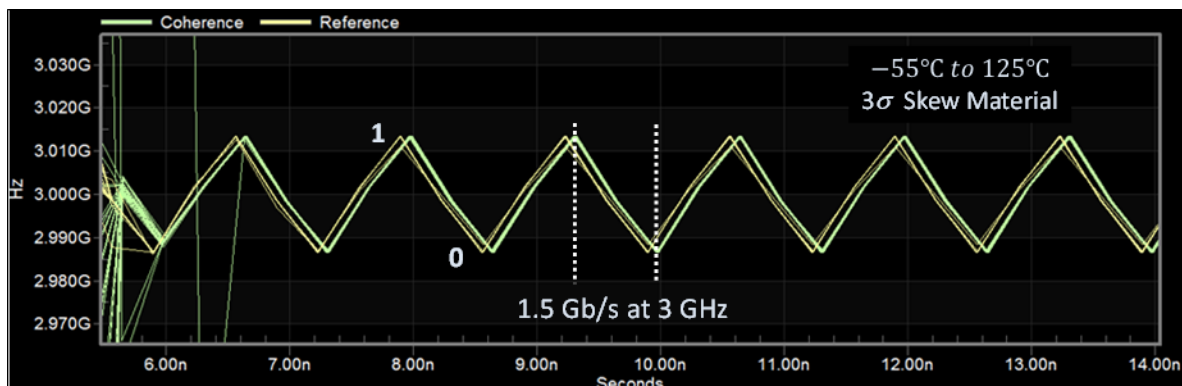


Figure 17. Ideal modulation, with bitrate at half of carrier frequency.

Ideal phase tracking of IL leads to the ideal phase modulation/demodulation of IW. No other existing physical link, with high bitrates, can be simulated as with IW, thus ensuring far greater design validation. Such a simulation is shown as modulated and demodulated signal transmitted and received across an entire IW physical link in Figure 18. IW can achieve bitrates at half of the transmit frequency, 1.5 Gb/s at 3 GHz transmit as shown in Figure 17.

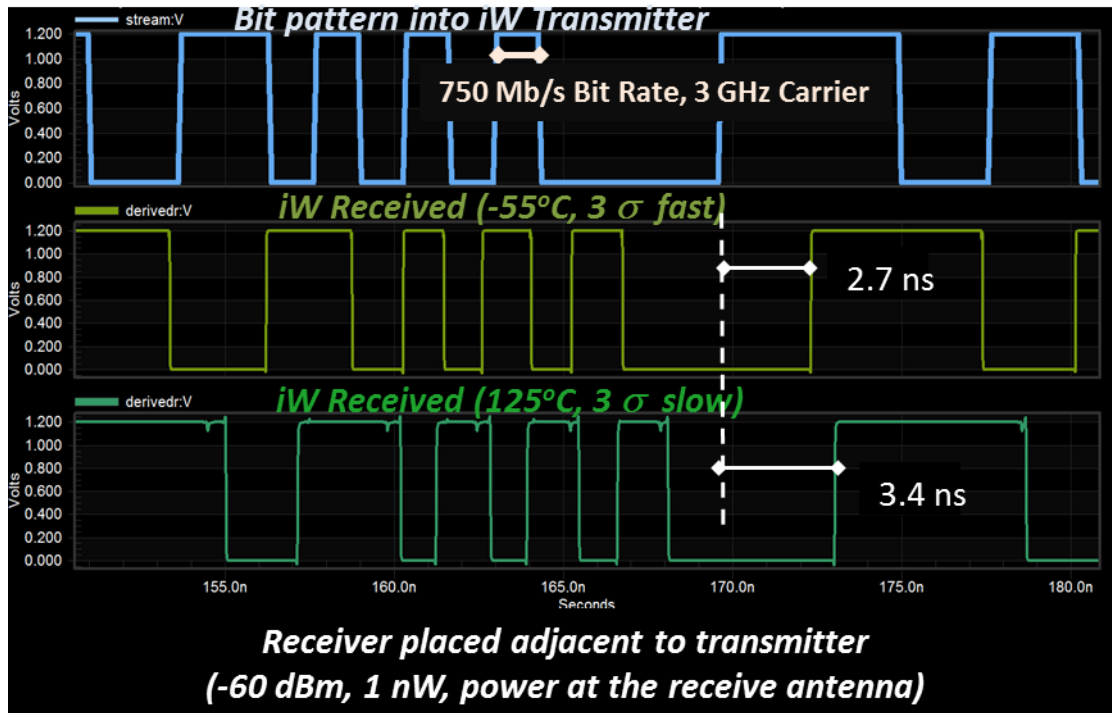


Figure 18. Negligible latencies from transmit to receive, transmitter and receiver adjacent to each other.