CHOOSE THE PATH OF LEAST RESISTANCE FOR YOUR DATA

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How much data does a farm generate daily?

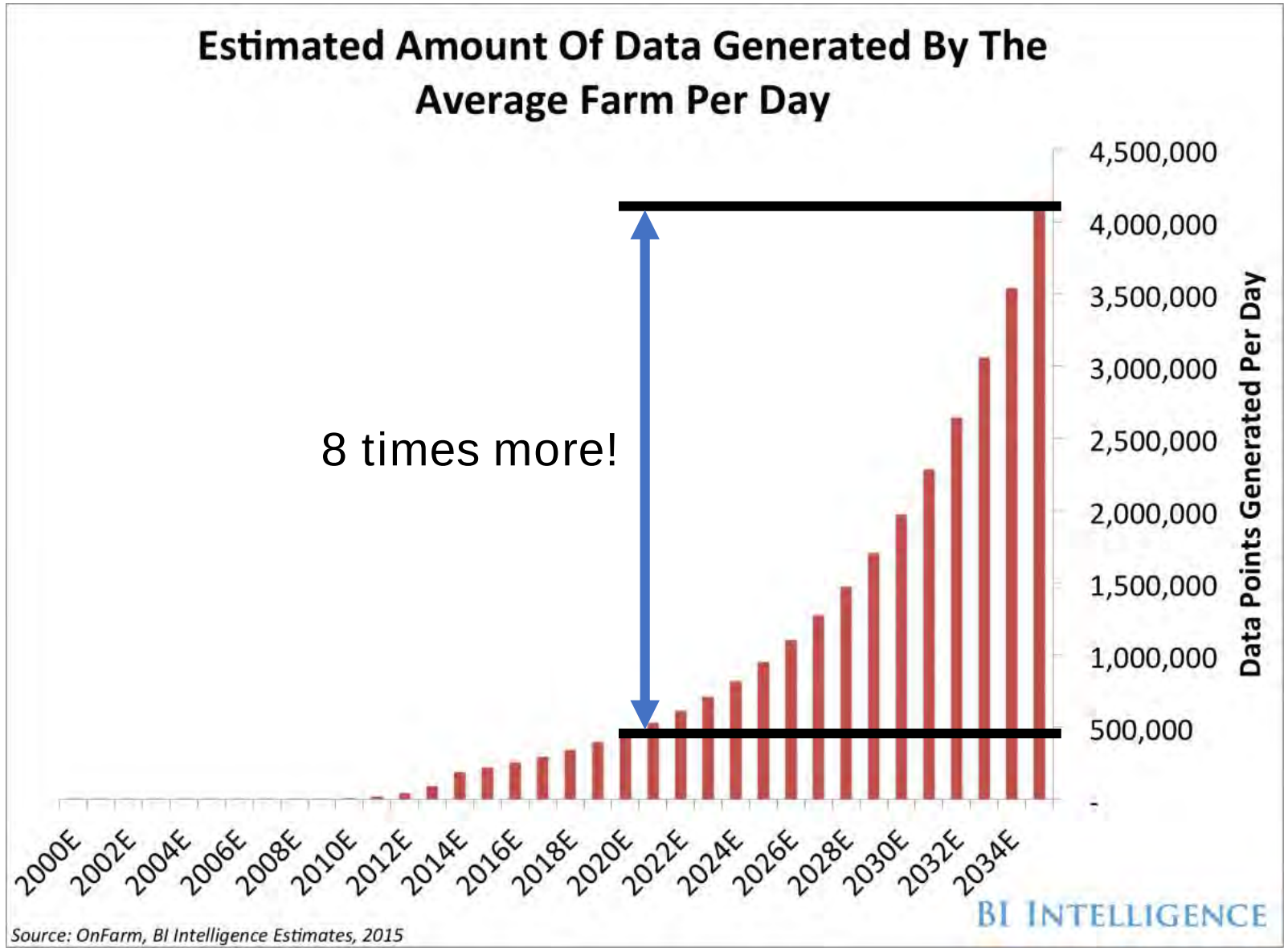
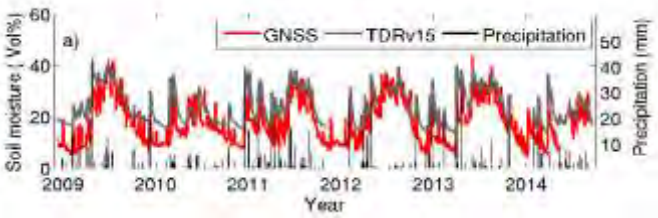


Image source: https://www.onfarm.com/iot-big-data-smart-farming-future-agriculture/

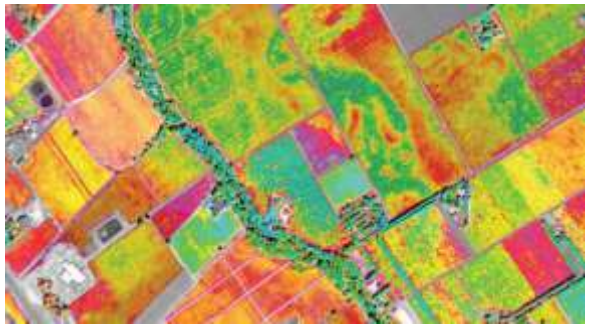
Traditional data



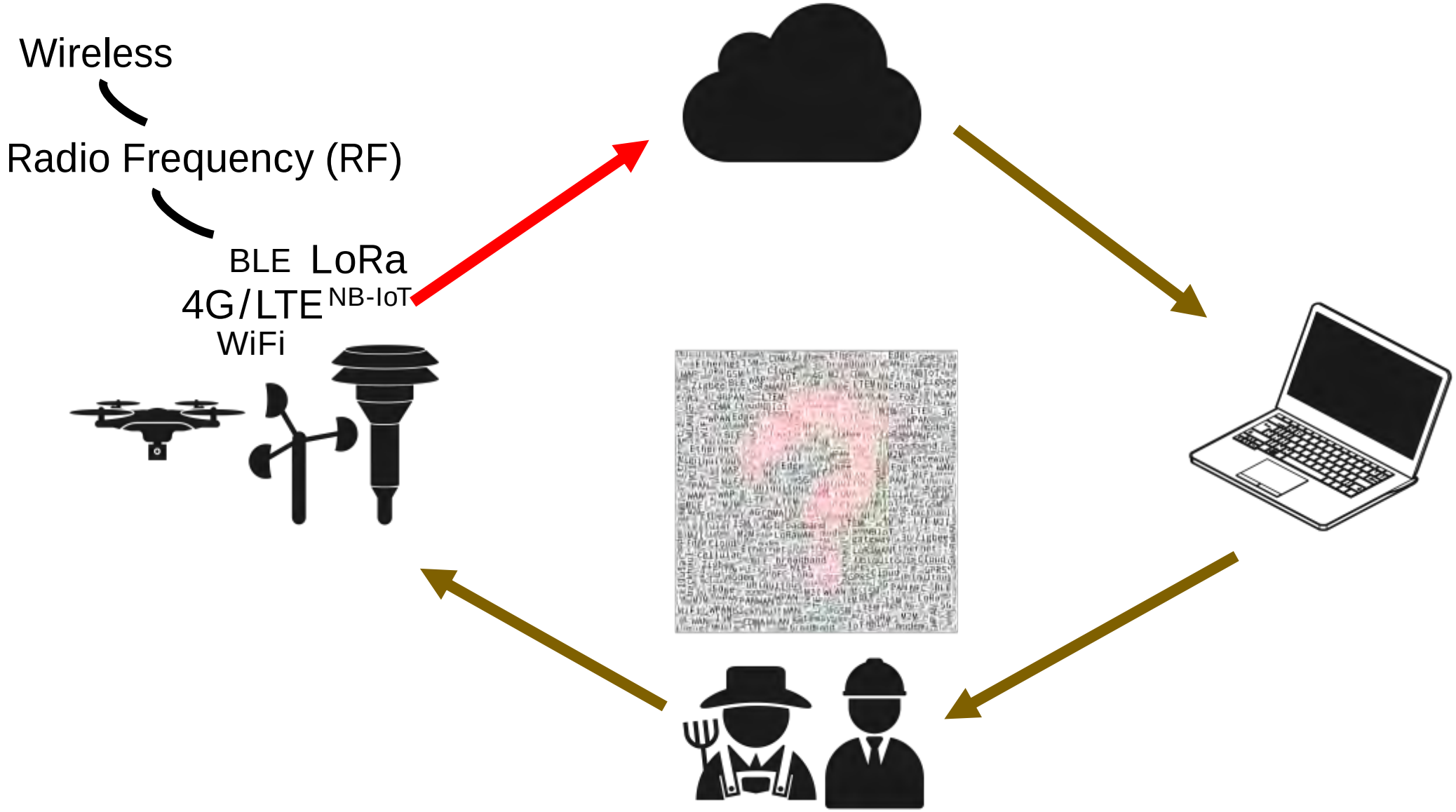
Image

Video

Topology



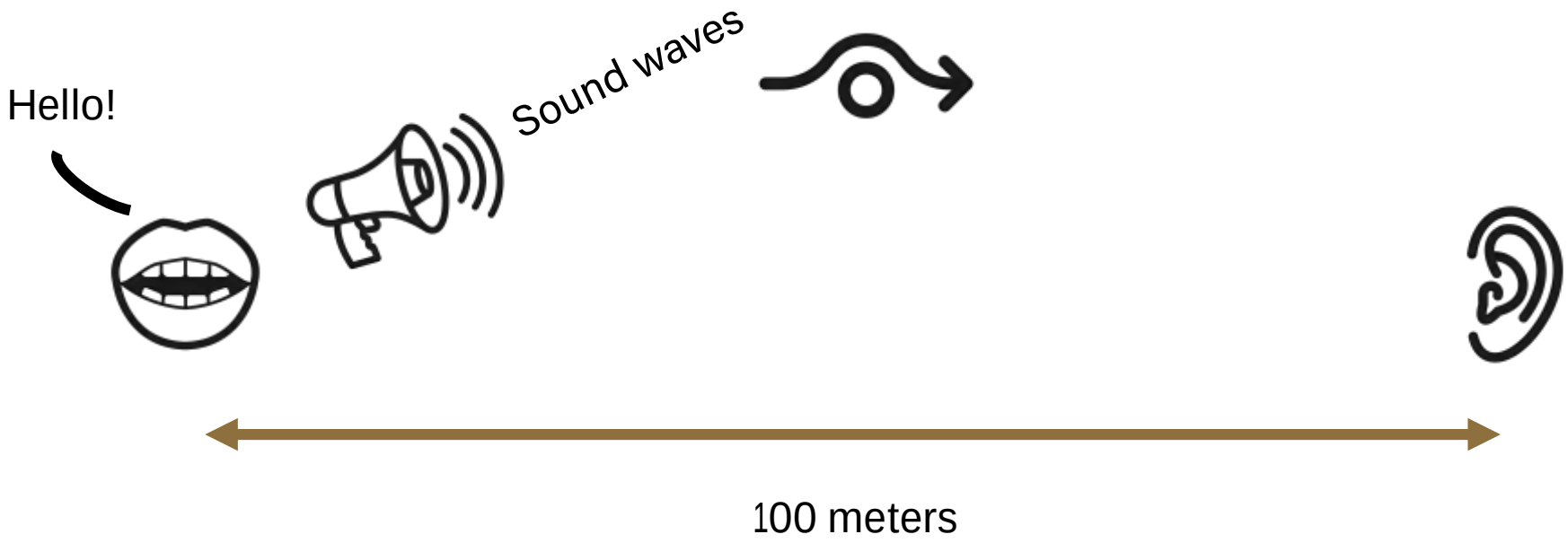
See References (slide 43) for image sources



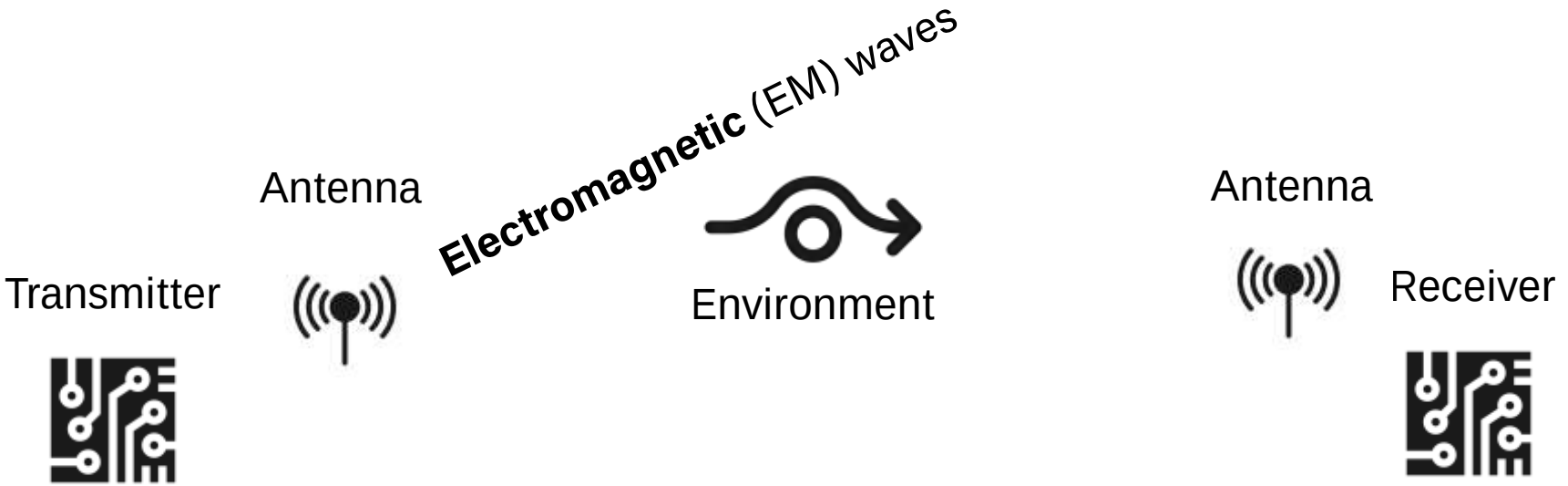
Word cloud generation source gist: https://gist.github.com/wang701/48c65a442ce3eb06ad3f3d5e4f4ec30a

Part I: RF Essentials

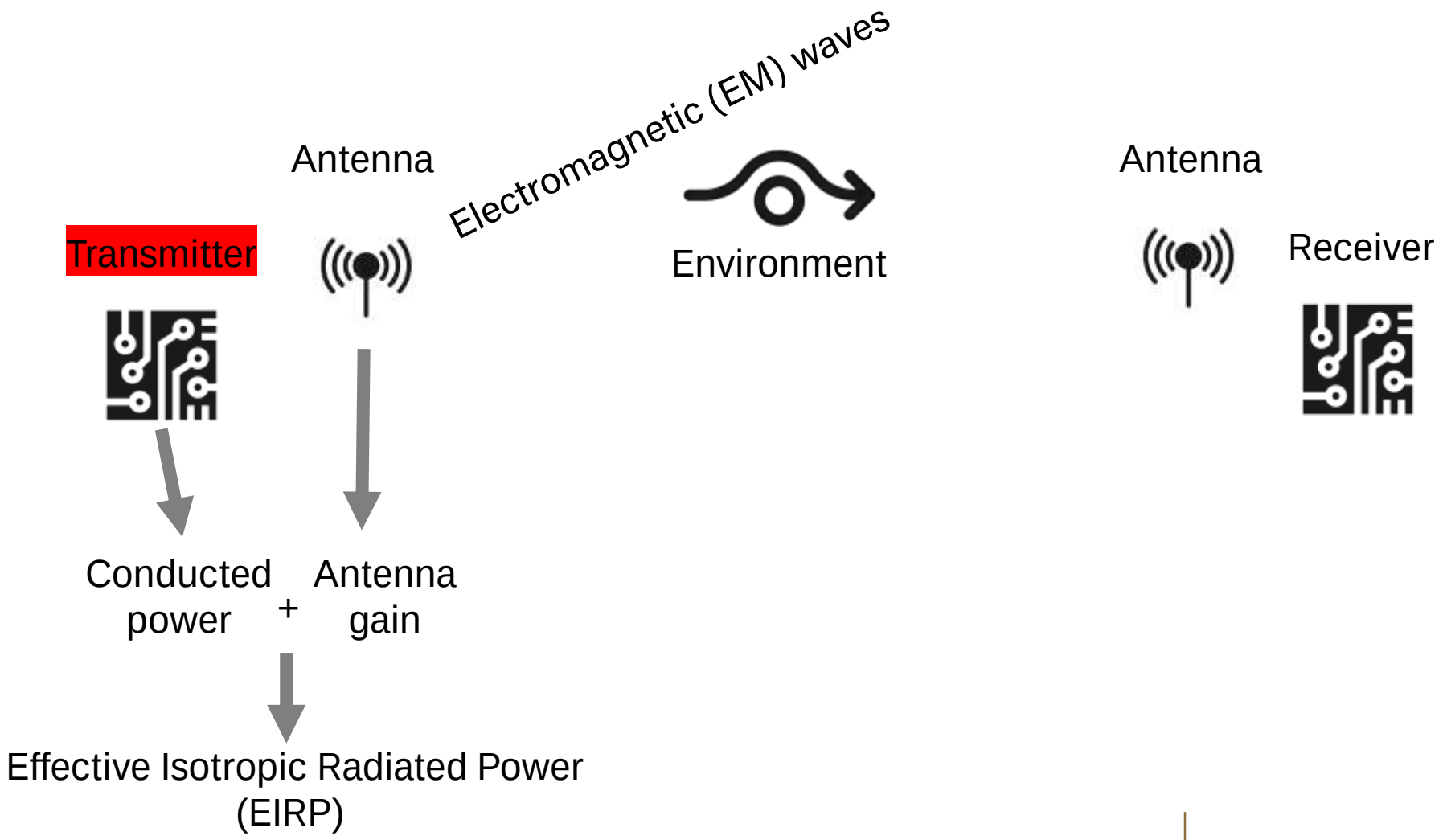
RF Essentials



Basic communication system



RF Essentials



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RF Essentials

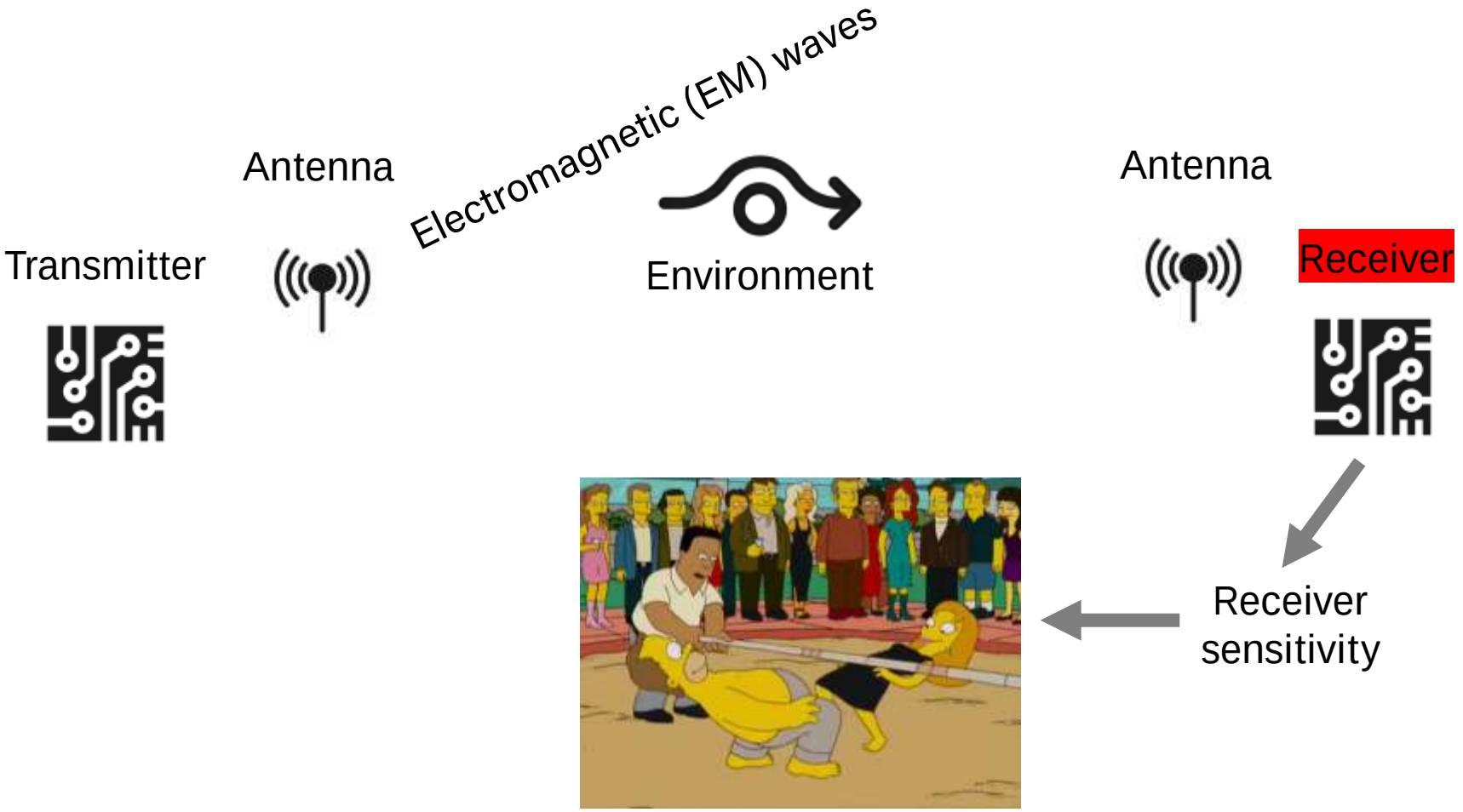

Image source: https://getyarn.io/yarn-clip/f71fe540-219a-4833-975e-19a4c87cf927

RF Essentials

Antenna

Electromagnetic (EM) waves

Antenna

Transmitter

Environment

Receiver

Omni-directional

Directional

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See References (slide 43) for image sources

RF Essentials

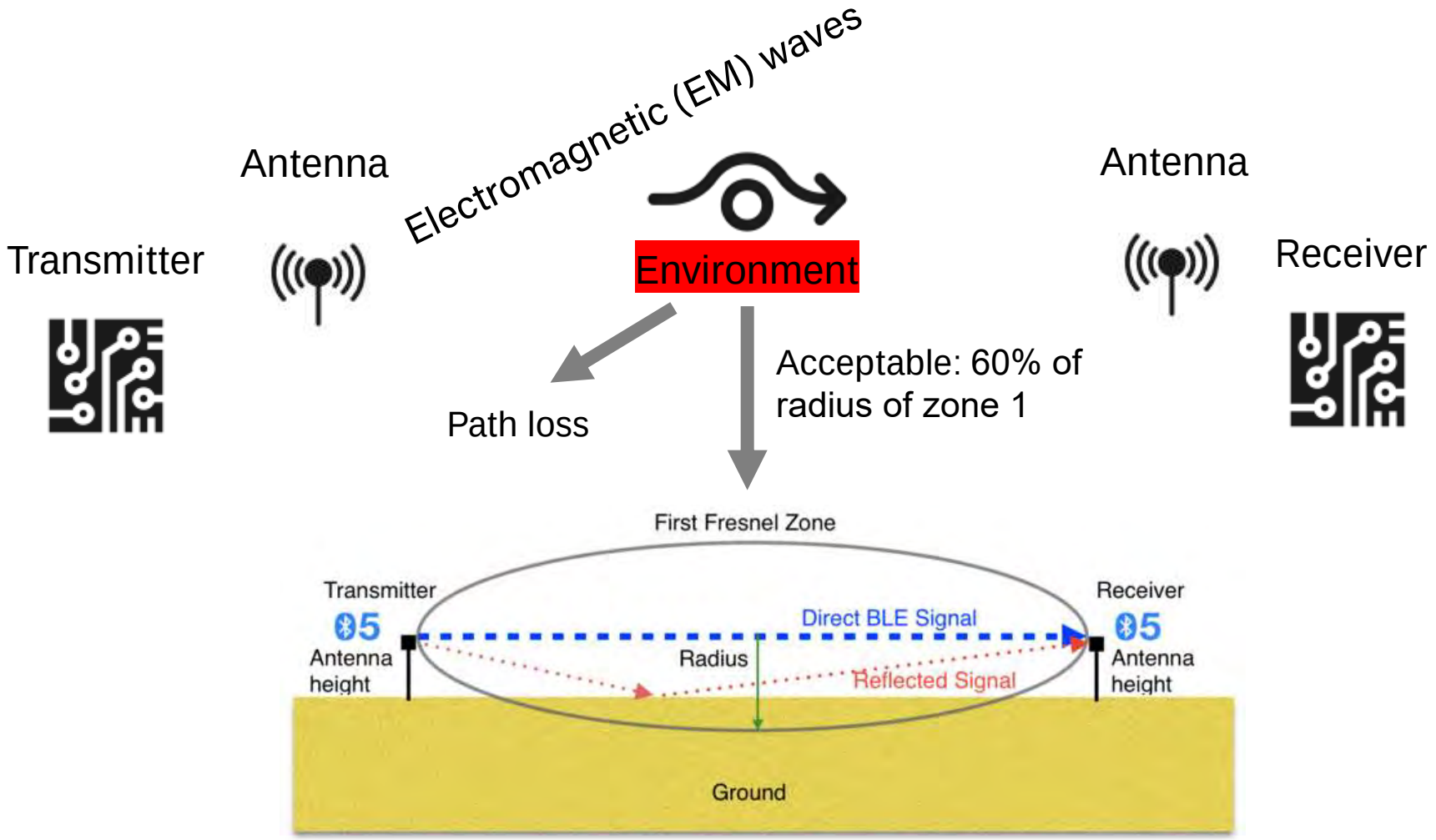


Image source: https://www.fanstel.com/blog/fresnel-zone-and-bluetooth-range

RF Essentials

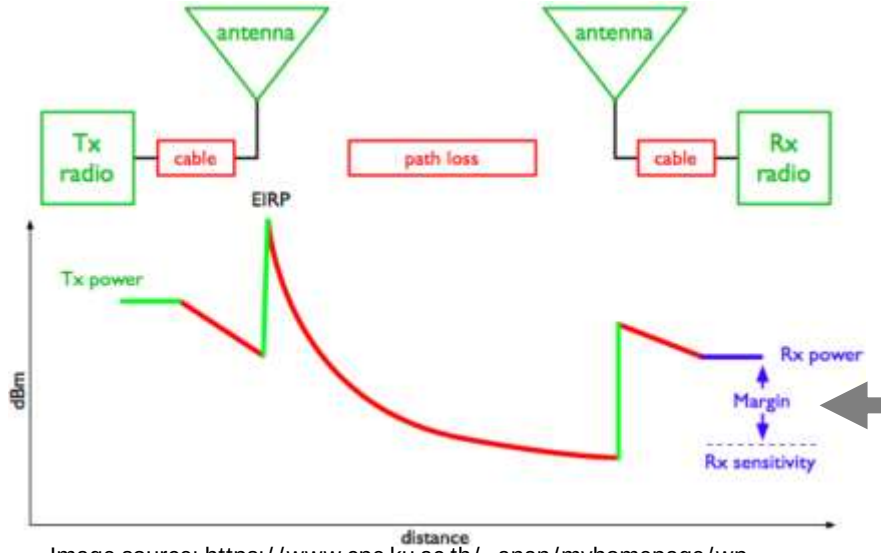
Antenna

Electromagnetic (EM) waves

Transmitter

Environment

Receiver



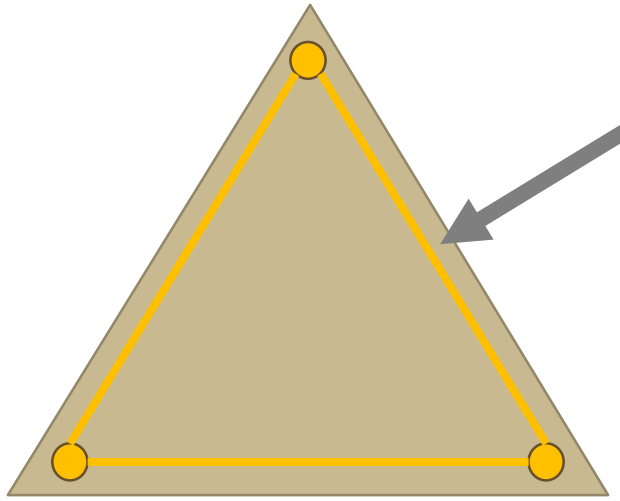
Link budget

Image source: https://www.cpe.ku.ac.th/~anan/myhomepage/wp-content/uploads/2018/02/2018-LoRAWAN-linkBudget-Calculation.pdf

RF Essentials

Lower -> better

Power



Ideal protocol

Data Rate

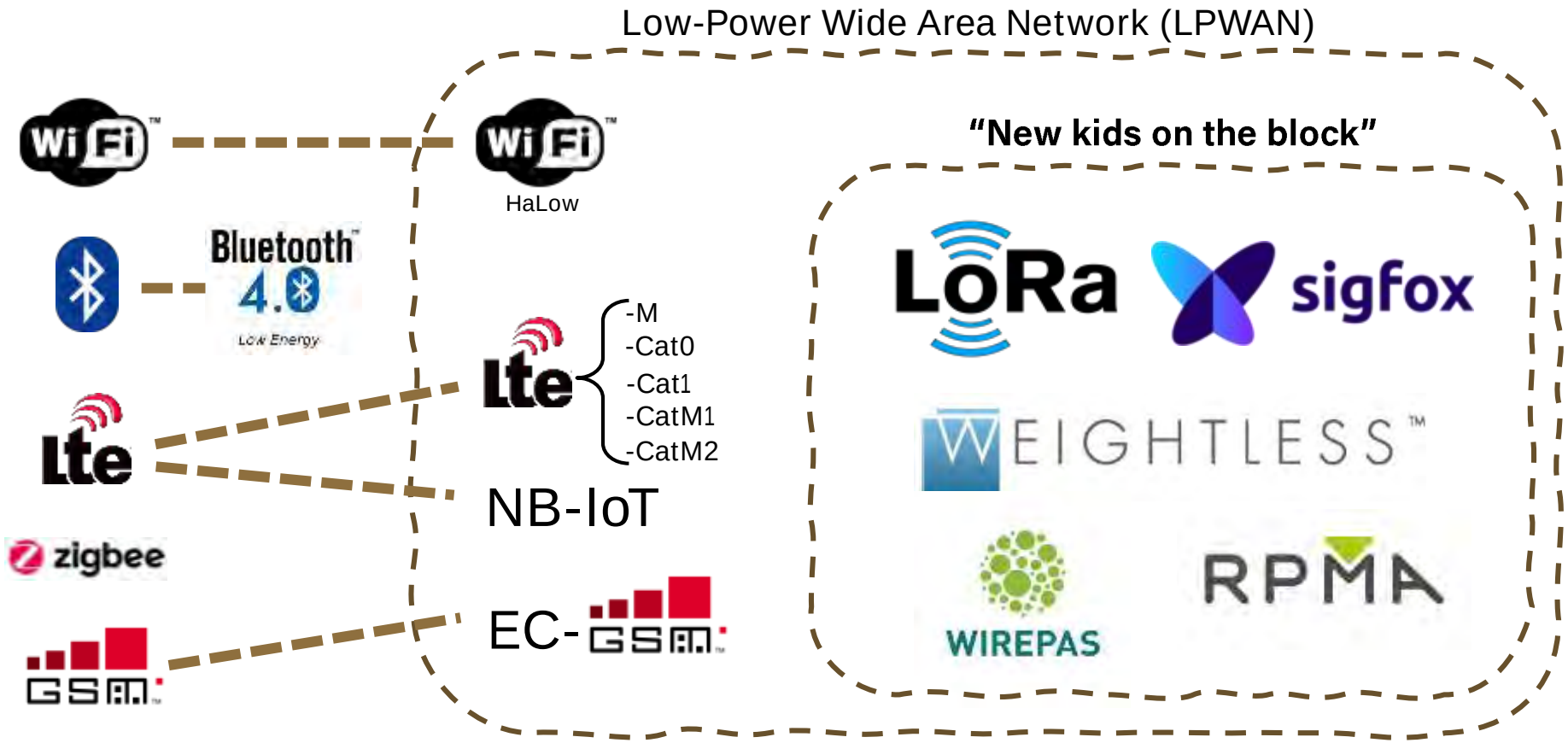
Higher -> better

Range

Longer -> better

Part II: Parameter Visualizations

Parameter Visualizations



Parameter Visualizations

Data rate vs. range

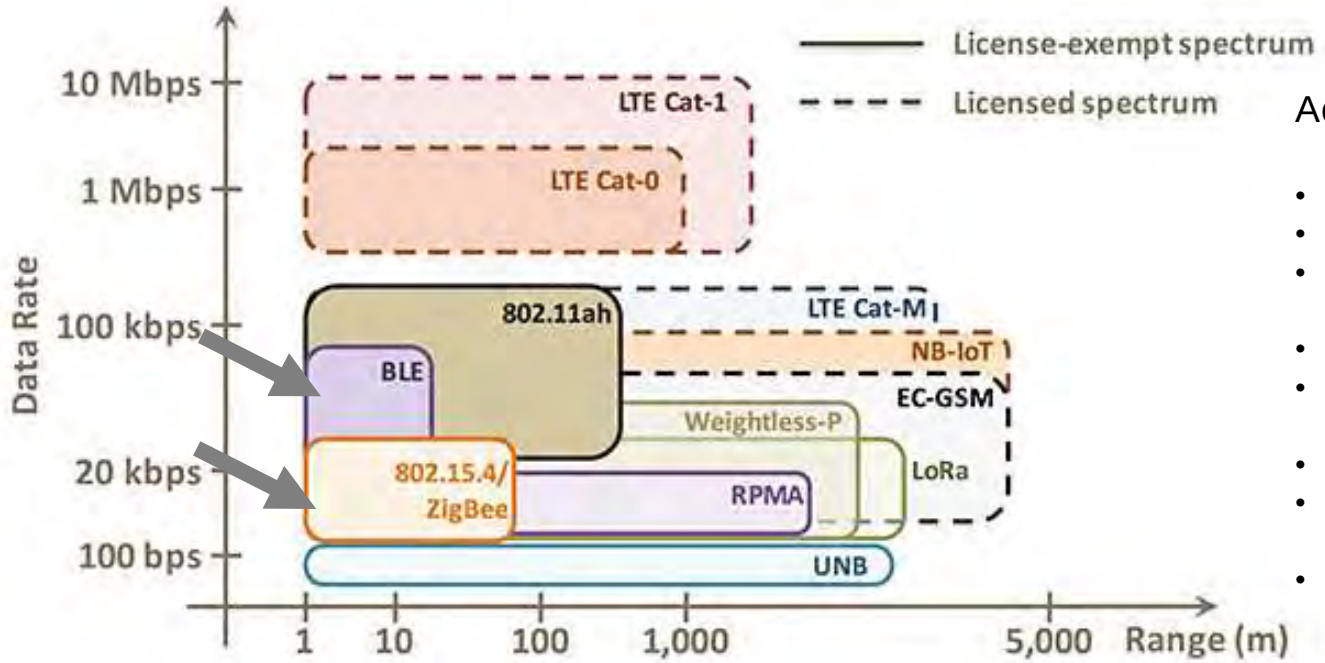


Image source: https://iotbusinessnews.com/2016/02/12/51954-the-great-iot-connectivity-race/

Acronyms:

- LTE – Long Time Evolution
- Cat – Category
- NB-IoT – Narrowband Internet of Things
- 802.11ah – WiFi HaLow
- EC-GSM – Extended Coverage Global System for Mobile Communications
- BLE – Bluetooth Low Energy
- RPMA – Random Phase Multiple Access
- UNB – Ultra Narrowband

Parameter Visualizations

Data rate vs. power consumption

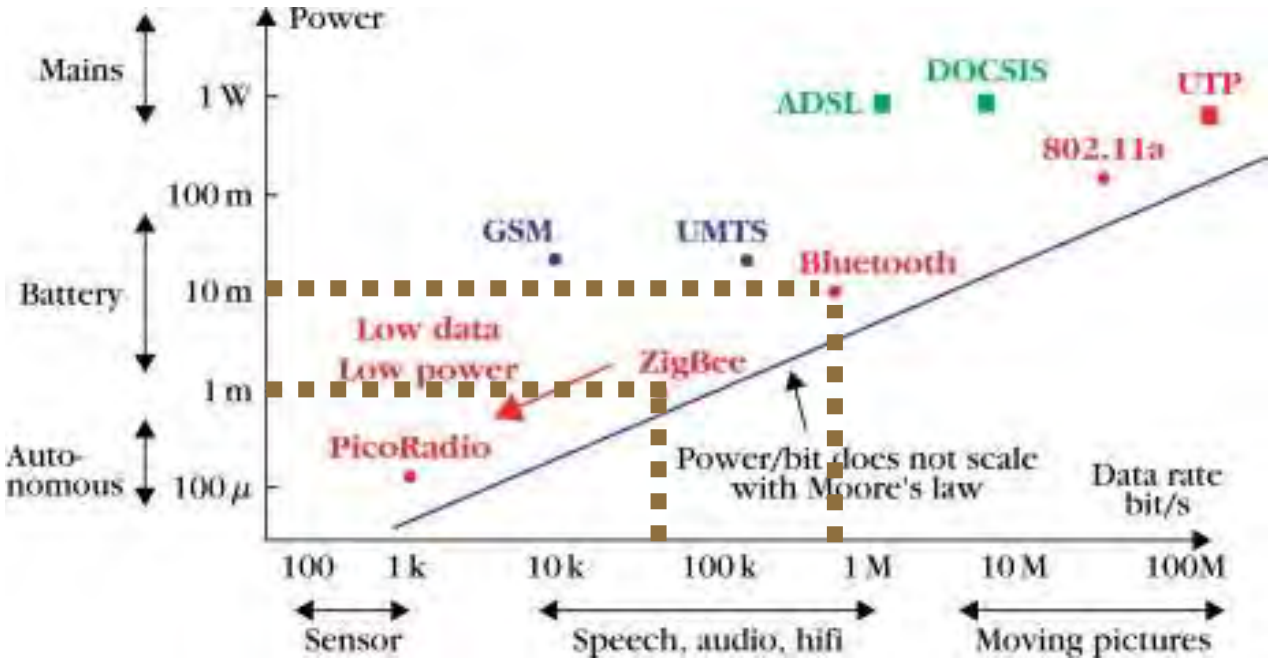
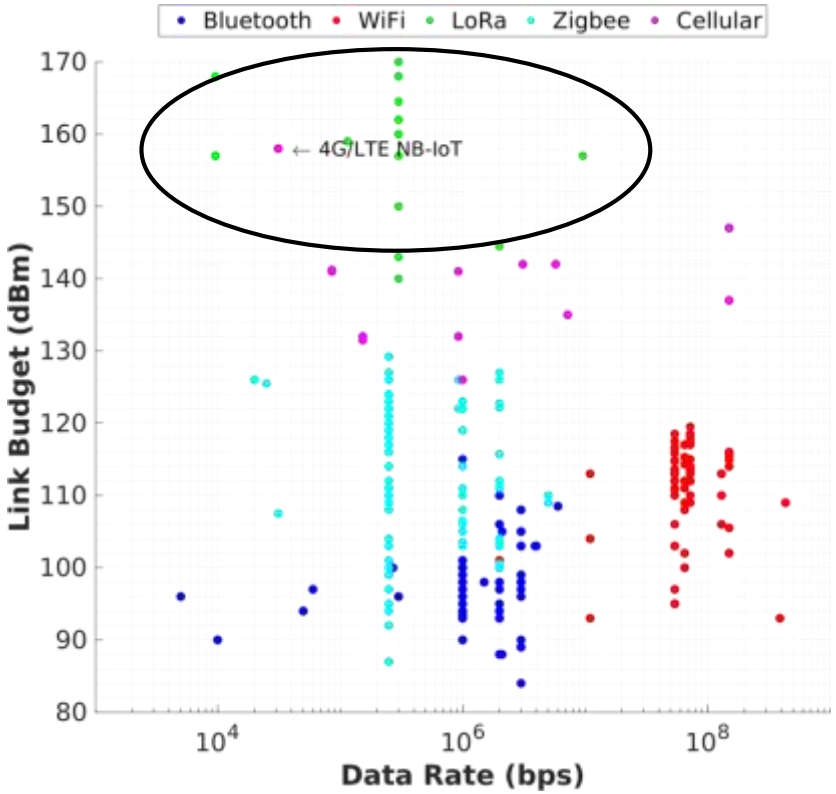
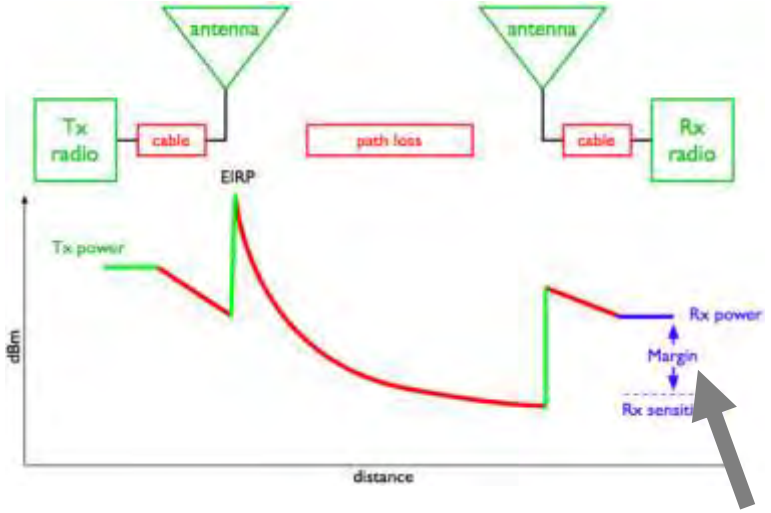


Image source: https://www.sciencedirect.com/science/article/pii/B9780123746337000239

Parameter Visualizations

Data rate vs. link budget

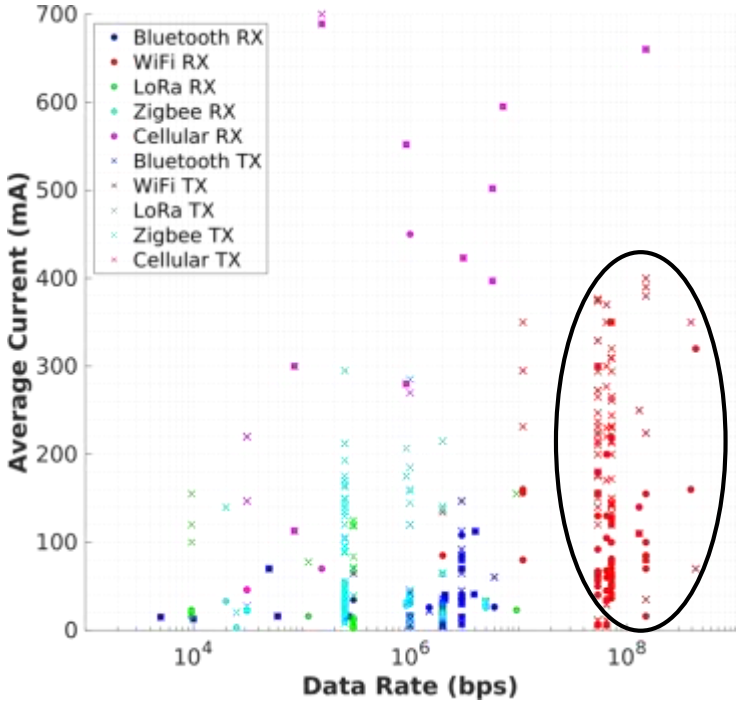


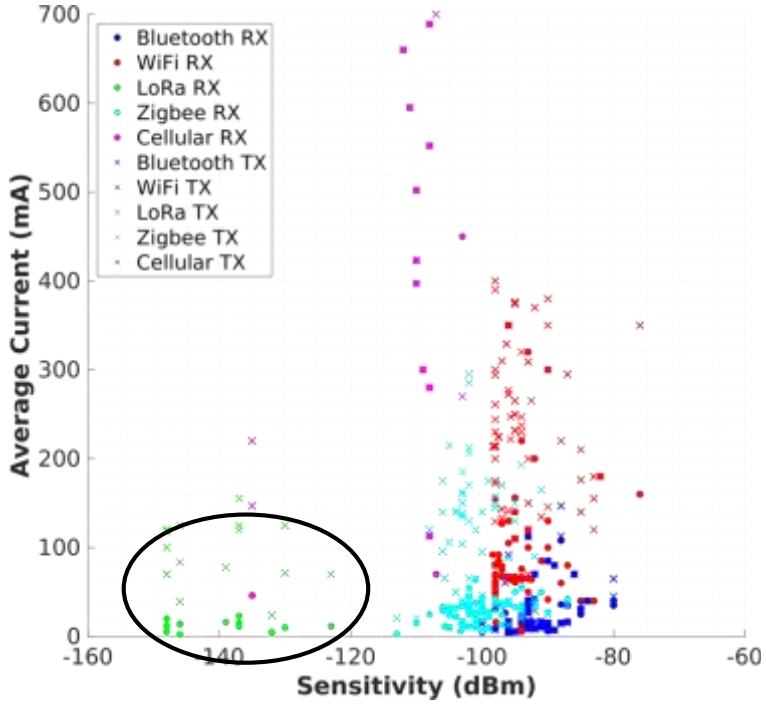


Link budget

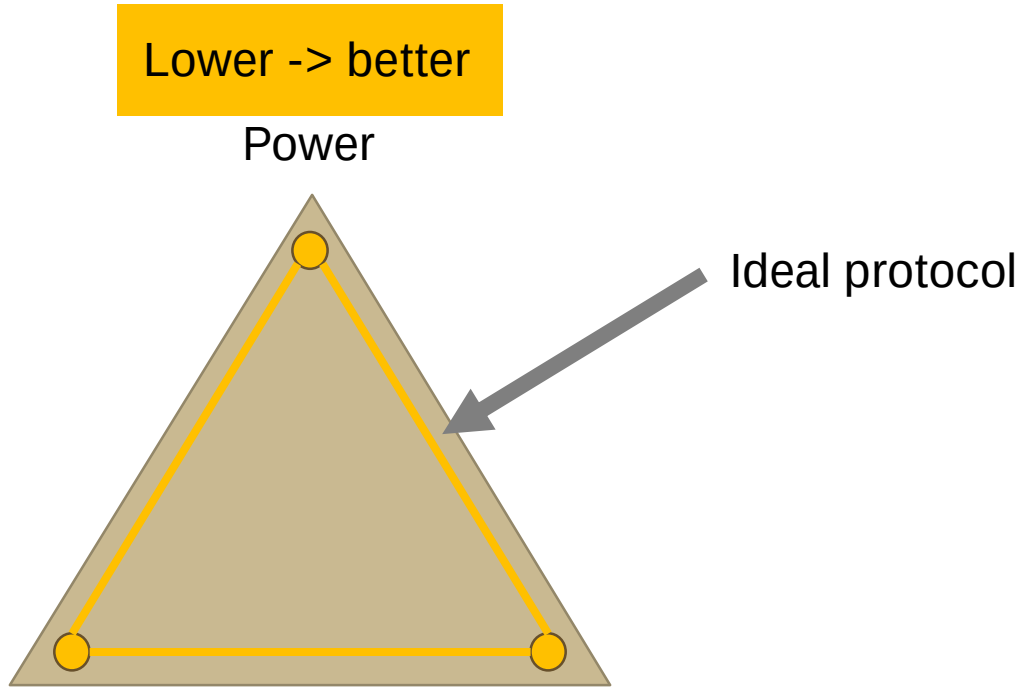
Parameter Visualizations

Data rate & sensitivity vs. average current draw





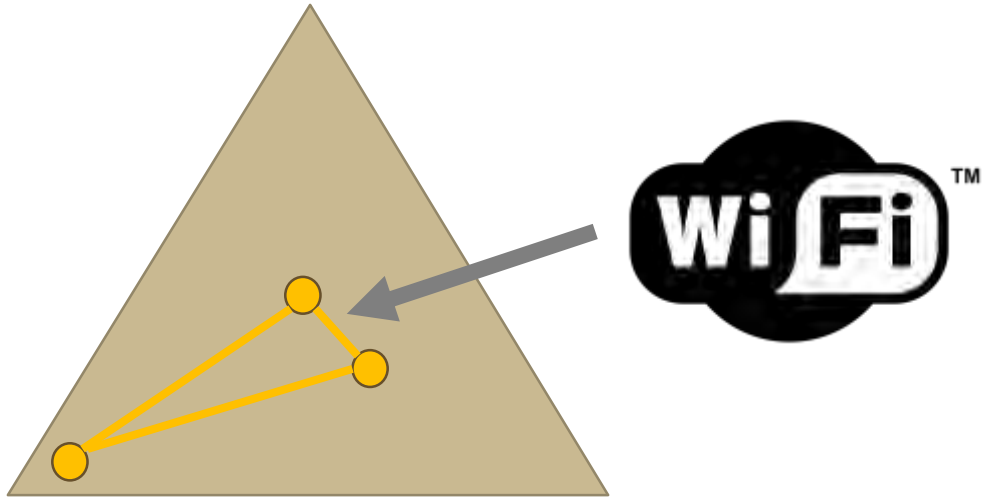
Parameter Visualizations



Parameter Visualizations

Lower -> better

Power



Data Rate

Range

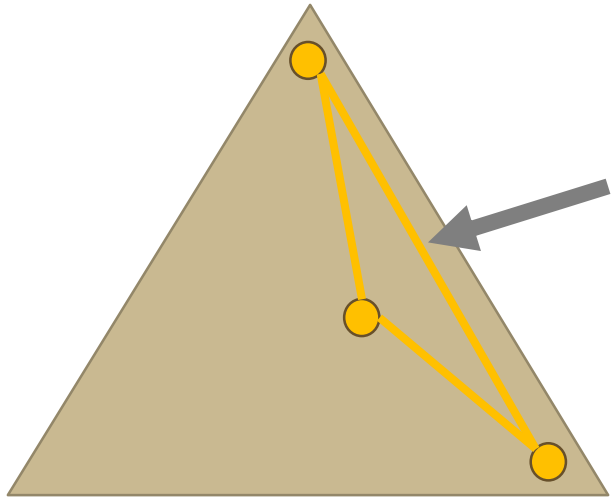
Higher -> better

Longer -> better

Parameter Visualizations

Lower -> better

Power



LoRa

Data Rate

Higher -> better

Range

Longer -> better

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Part III: DIY Comparisons

DIY Comparisons

Simple exercise

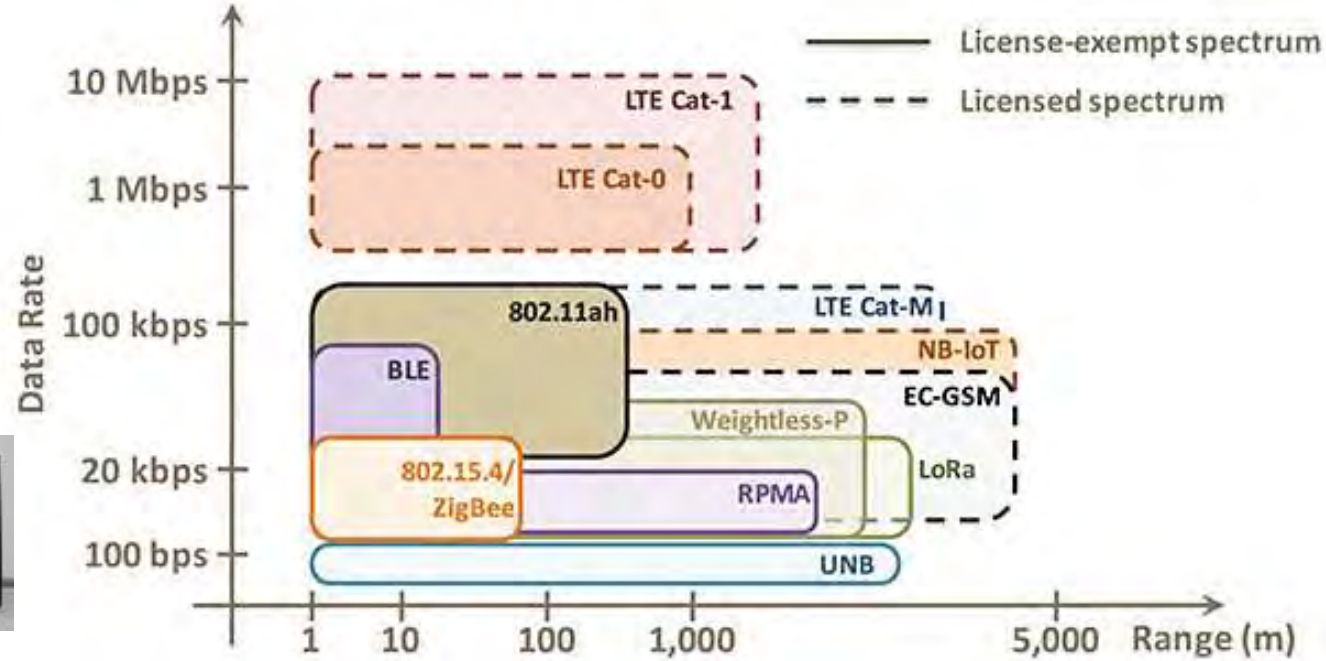


Image source: https://iotbusinessnews.com/2016/02/12/51954-the-great-iot-connectivity-race/

How about TV White Space (TVWS)?

DIY Comparisons

Compare with real data

	AFS Connect™ Magnum™ Seri	John Deere
	Magnum 180 Wheeled, AFS C	6195M (2020-Present)
Engine Performance		
Advertised Engine Power, Rated, hp (kW)	180 (132)	195 (143)
Maximum Engine Power, hp (kW)	225 (165)	206 (151)
Rated Engine Speed, rpm	2100	2100
Power Boost, hp (kW)	45 (33)	11 (8)
Fuel Tank capacity, gal (L)	160 (600)	86 (325)
Diesel Exhaust Fluid (DEF) tank capacity, gal (L)	17.5 (66)	5.3 (20)

CASE IH Compare Specifications: https://www.caseih.com/northamerica/en-us/compare-specifications

DIY Comparisons

Crawl information from datasheet(s)

GEN 3 RURALCONNECT® SPECIFICATIONS

Below are examples of different distances and modulation settings to show throughputs and link margin in a single 6 MHz channel. With an additional radio module in the client station, use of two 6 MHz channels would deliver end-user throughputs ~twice that of the 6 MHz channel. Note that the OTA data rate has to be divided between uplink and downlink, e.g., if 80/20, then 24 Mbps = 19 DL and 5 UL. To understand how many CPE's can be used with a Base station, divide the base station capacity by the number of CPE's multiplied by the contention ratio (typically 6). For example, Base cap = 24 x 3 = 72Mb/s. 48 CPEs x 6 = 72/244 = 2.5Mbps for 48 active CPE's.

Modulation and Coding	OTA Data Rate in Mbps	Range in km*	Base Ant Gain in dBi	CPE Ant Gain in dBi	Frequency in MHz	Base EIRP in dBm	Free Space Loss in dB	RX Signal in dBm	CPE Sens in dBm	Link Margin in dB**	Rayleigh Fading %
QPSK 3/4	5.4	33	7.8	10.3	569	28.5	118.0	-79.7	-96.4	16.7	98.66
16 QAM 3/4	10.8	16	7.8	10.3	545	28.5	111.3	-73.0	-89.4	16.4	98.55
64QAM 5/6	18	5.0	7.8	10.3	521	28.5	100.8	-62.5	-79.1	16.6	98.61
256QAM5/6	24	2.5	7.8	10.3	473	28.5	94.0	-55.7	-72.2	16.5	98.60

*The distance is optimized for 98% availability

** if the path is unobstructed

Datasheet source: http://www.carlsonwireless.com/wp-content/uploads/2018/04/RuralConnect-Gen3-US-03-28a-18-Print-Book-r.pdf

DIY Comparisons

Data rate vs. range

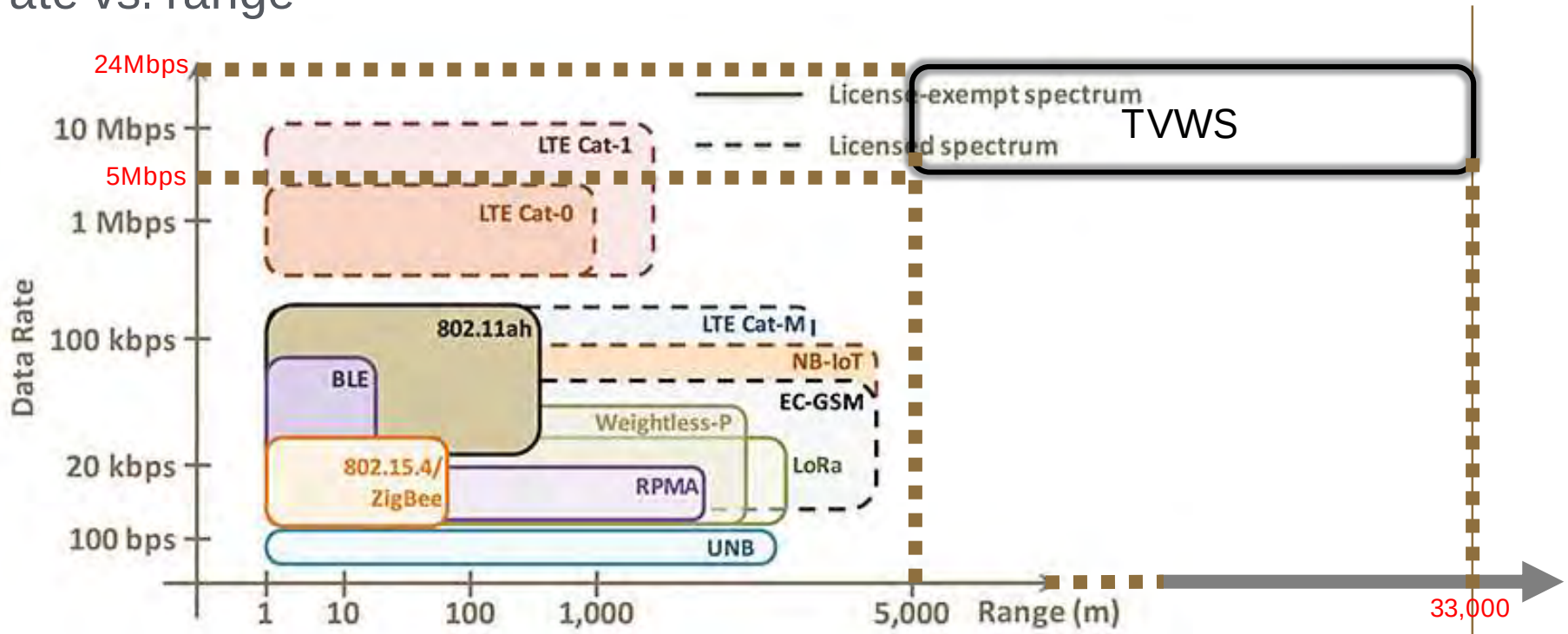


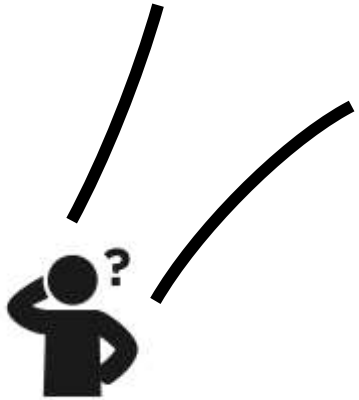
Image source: https://iotbusinessnews.com/2016/02/12/51954-the-great-iot-connectivity-race/

Wow, TVWS is better than most of these!

DIY Comparisons

Real-life scenario

I want to test some weather stations in one of my fields. Node data will be uploaded to my gateway device in my farm office 1 mile away once per day and I want the nodes to last at least 4 months on a 1000 mAh battery.



	Bluetooth Low Energy (BLE)	Zigbee	LoRa	WiFi
Module Name	Nordic Semiconductor nRF52840	XBee 3 Pro Module	Semtech SX1276	Expressif ESP8266EX
Unit Cost	$7.08	$16.21	$4.16	$3.20

DIY Comparisons

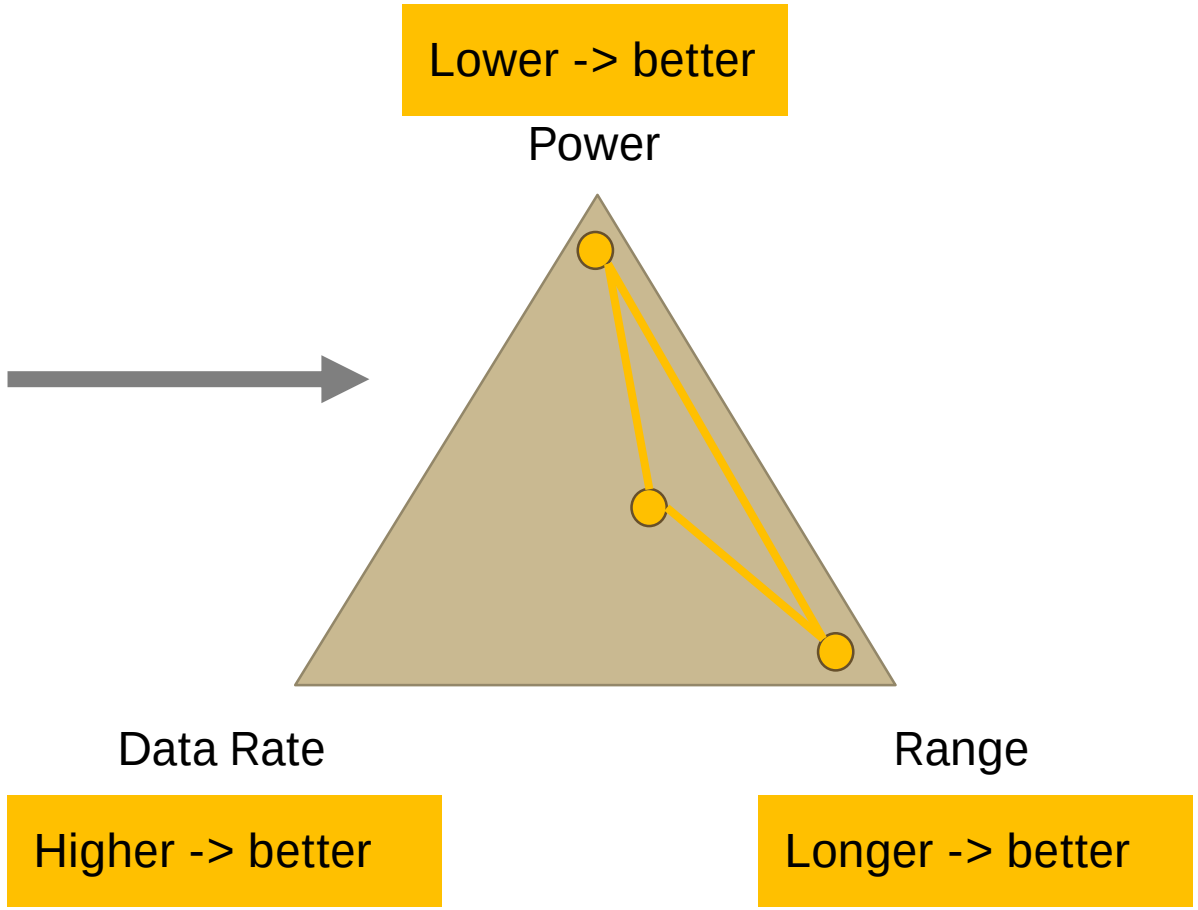
Goal

"Weather stations"

"1 mile"

"Once per day"

"At least 4 months with a 1000 mAh battery"



DIY Comparisons

Strategy: start with an empty table

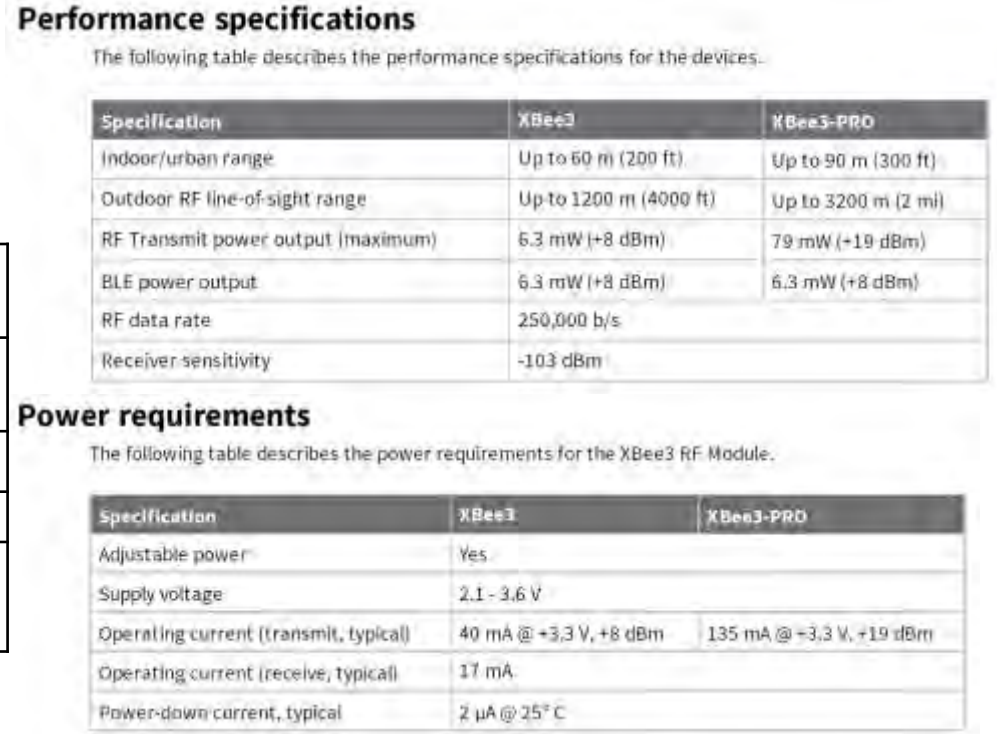
Type	BLE	Zigbee	LoRa	WiFi
Name	Nordic nRF52840	XBee 3 Pro Module	Semtech SX1276	Expressif ESP8266EX
Data Rate	?	?	?	?
Range (m)	?	?	?	?
Average Power Consumption (mA in Tx Mode)	?	?	?	?

DIY Comparisons

Some datasheets already have what we need

Example: Zigbee module

Type	BLE	Zigbee	LoRa	WiFi
Name	Nordic nRF52840	XBee 3 Pro Module	Semtech SX1276	Expressif ESP8266EX
Data Rate	?		?	?
Range (m)	?		?	?
Average Power Consumption (mA in Tx Mode)	?		?	?



Performance specifications

The following table describes the performance specifications for the devices.

Specification	XBee3	XBee3-PRO
Indoor/urban range	Up to 60 m (200 ft)	Up to 90 m (300 ft)
Outdoor RF line-of-sight range	Up to 1200 m (4000 ft)	Up to 3200 m (2 mi)
RF Transmit power output (maximum)	6.3 mW (+8 dBm)	79 mW (+19 dBm)
BLE power output	6.3 mW (+8 dBm)	6.3 mW (+8 dBm)
RF data rate	250,000 b/s	
Receiver sensitivity	-103 dBm	

Power requirements

The following table describes the power requirements for the XBee3 RF Module.

Specification	XBee3	XBee3-PRO
Adjustable power	Yes	
Supply voltage	2.1 - 3.6 V	
Operating current (transmit, typical)	40 mA @ +3.3 V, +8 dBm	135 mA @ +3.3 V, +19 dBm
Operating current (receive, typical)	17 mA	
Power-down current, typical	2 µA @ 25° C	

Datasheet source: https://www.digi.com/resources/documentation/digidocs/pdfs/90001543.pdf

DIY Comparisons

For some, information is not readily available

Example: BLE module

Type	BLE	Zigbee	LoRa	WiFi
Name	Nordic nRF52840	XBee 3 Pro Module	Semtech SX1276	Expressif ESP8266EX
Data Rate	?		?	?
Range (m)	?		?	?
Average Power Consumption (mA in Tx Mode)			?	?

6.20.15.2 Radio current consumption (transmitter)

Symbol	Description	Min.	Typ.	Max.	Units
	TX only run current (DC/DC, 3 V) P_{RF} = +8 dBm		14.8		mA
	TX only run current P_{RF} = +8 dBm		32.7		mA
	TX only run current (DC/DC, 3 V) P_{RF} = +4 dBm		9.6		mA
	TX only run current P_{RF} = +4 dBm		21.4		mA
	TX only run current (DC/DC, 5 V, REG0 out = 3.3 V) P_{RF} = 0 dBm		3.0		mA
	TX only run current (DC/DC, 5 V, REG0 out = 1.8 V) P_{RF} = 0 dBm		3.0		mA
	TX only run current (DC/DC, 3 V) P_{RF} = 0 dBm		4.8		mA
	TX only run current P_{RF} = 0 dBm		10.6		mA
	TX only run current DC/DC, 3 V P_{RF} = -4 dBm		3.1		mA
	TX only run current P_{RF} = -4 dBm		8.1		mA
	TX only run current DC/DC, 3 V P_{RF} = -8 dBm		3.3		mA
	TX only run current P_{RF} = -8 dBm		7.2		mA
	TX only run current DC/DC, 3 V P_{RF} = -12 dBm		3.0		mA
	TX only run current P_{RF} = -12 dBm		6.4		mA
	TX only run current DC/DC, 3 V P_{RF} = -16 dBm		2.8		mA
	TX only run current P_{RF} = -16 dBm		6.0		mA
	TX only run current DC/DC, 3 V P_{RF} = -20 dBm		2.7		mA
	TX only run current P_{RF} = -20 dBm		5.6		mA
	TX only run current DC/DC, 3 V P_{RF} = -40 dBm		2.3		mA
	TX only run current P_{RF} = -40 dBm		4.6		mA
	TX start-up current DC/DC, 3 V, P_{RF} = 4 dBm		5.2		mA
	TX start-up current, P_{RF} = 4 dBm		11.0		mA

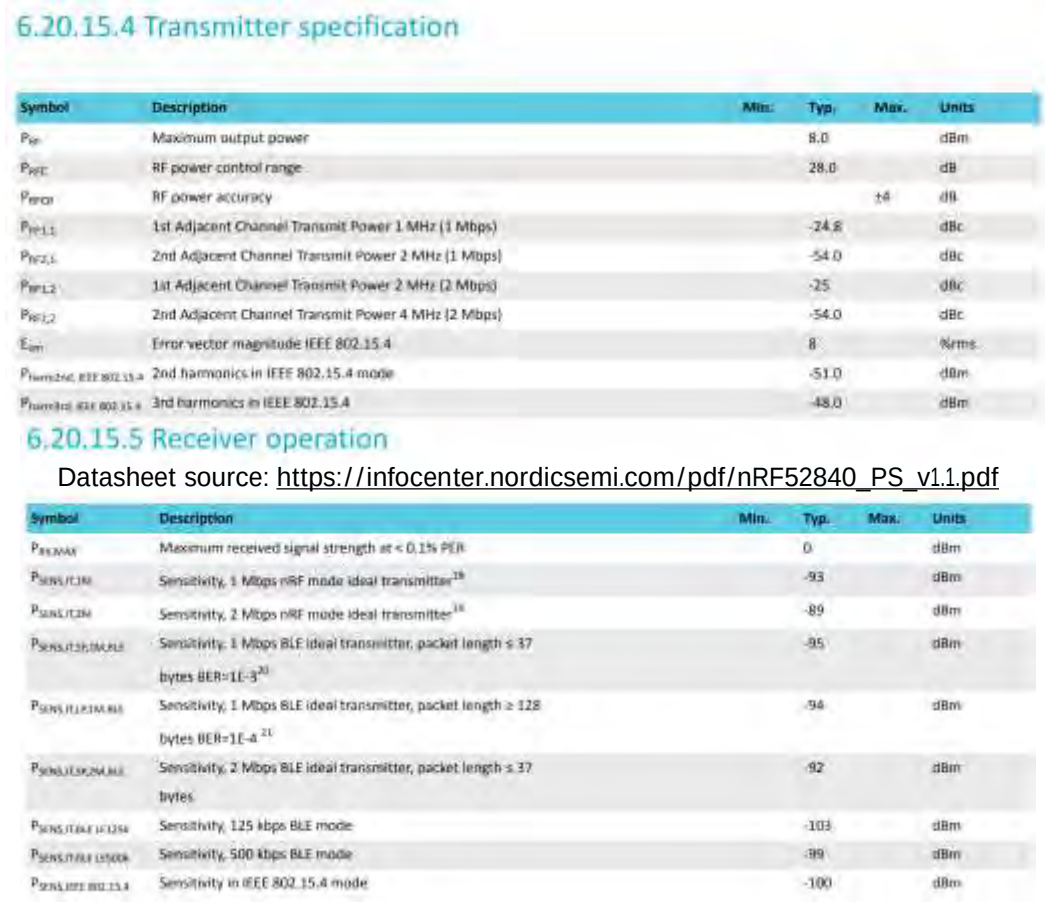
Datasheet source: https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf

DIY Comparisons

For some, information is not readily available

Example: BLE module

Type	BLE	Zigbee	LoRa	WiFi
Name	Nordic nRF52840	XBee 3 Pro Module	Semtech SX1276	Expressif ESP8266EX
Data Rate			?	?
Range (m)			?	?
Average Power Consumption (mA in Tx Mode)			?	?



6.20.15.4 Transmitter specification

Symbol	Description	Min.	Typ.	Max.	Units
P_{RF}	Maximum output power		8.0		dBm
P_{RFC}	RF power control range		28.0		dB
P_{RFCR}	RF power accuracy			±4	dB
$P_{RF1.1}$	1st Adjacent Channel Transmit Power 1 MHz (1 Mbps)		-24.8		dBc
$P_{RF2.1}$	2nd Adjacent Channel Transmit Power 2 MHz (1 Mbps)		-54.0		dBc
$P_{RF1.2}$	1st Adjacent Channel Transmit Power 2 MHz (2 Mbps)		-25		dBc
$P_{RF2.2}$	2nd Adjacent Channel Transmit Power 4 MHz (2 Mbps)		-54.0		dBc
E_{VM}	Error vector magnitude IEEE 802.15.4		8		%rms
$P_{harm2nd,\ IEEE\ 802.15.4}$	2nd harmonics in IEEE 802.15.4 mode		-51.0		dBm
$P_{harm3rd,\ IEEE\ 802.15.4}$	3rd harmonics in IEEE 802.15.4		-48.0		dBm

6.20.15.5 Receiver operation

Datasheet source: https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf

Symbol	Description	Min.	Typ.	Max.	Units
$P_{RX,MAX}$	Maximum received signal strength at < 0.1% PER		0		dBm
$P_{SENS,1M}$	Sensitivity, 1 Mbps nRF mode ideal transmitter[19]		-93		dBm
$P_{SENS,2M}$	Sensitivity, 2 Mbps nRF mode ideal transmitter[19]		-89		dBm
$P_{SENS,1M,BLE}$	Sensitivity, 1 Mbps BLE ideal transmitter, packet length ≤ 37 bytes BER=1E-3[20]		-95		dBm
$P_{SENS,1M,BLE}$	Sensitivity, 1 Mbps BLE ideal transmitter, packet length ≥ 128 bytes BER=1E-4[21]		-94		dBm
$P_{SENS,2M,BLE}$	Sensitivity, 2 Mbps BLE ideal transmitter, packet length ≤ 37 bytes		-92		dBm
$P_{SENS,125K}$	Sensitivity, 125 kbps BLE mode		-103		dBm
$P_{SENS,500K}$	Sensitivity, 500 kbps BLE mode		-99		dBm
$P_{SENS,IEEE\ 802.15.4}$	Sensitivity in IEEE 802.15.4 mode		-100		dBm

Datasheet source: https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf

DIY Comparisons

Range calculation

- Free-Space Path Loss (FSPL) model
  - Path loss in an obstacle-free, Line-of-Sight (LoS) path in free space

- Formula
  - $\mathrm{FSPL(dB)} = \text{link budget} - 30 = 20\log_{10}(D) + 20\log_{10}(f) + 92.45$
  - *D* in kilometers, *f* in GHz

$$\Longrightarrow D = 10^{\frac{\text{link budget} - 30 - 92.45 - 20\log_{10}(f)}{20}}$$

DIY Comparisons

For some, information is not readily available

Example: BLE module

Type	BLE	Zigbee	LoRa	WiFi
Name	Nordic nRF52840	XBee 3 Pro Module	Semtech SX1276	Expressif ESP8266EX
Data Rate			?	?
Range (m)			?	?
Average Power Consumption (mA in Tx Mode)			?	?

Given:

$$R_1 = 1\text{Mbps}, R_2 = 2\text{Mbps}, R_3 = 125\text{kbps}, R_4 = 250\text{kbps}.$$
$$P_{TX} = 8.0\text{dBm}.$$
$$P_{R,S1} = -93\text{dBm}, P_{R,S2} = -89\text{dBm},$$
$$P_{R,S3} = -103\text{dBm}, P_{R,S4} = -99\text{dBm}.$$

We can compute 1) link budgets and 2) distances:

$$\Longrightarrow D = 10^{\frac{\text{link budget} - 30 - 92.45 - 20\log_{10}(f)}{20}}$$

Datasheet source: https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf

6.20.15.4 Transmitter specification

Symbol	Description	Min.	Typ.	Max.	Units
P_{RF}	Maximum output power		8.0		dBm
P_{RFC}	RF power control range		28.0		dB
P_{error}	RF power accuracy			±4	dB
$P_{RF1,1}$	1st Adjacent Channel Transmit Power 1 MHz (1 Mbps)		-24.8		dBc
$P_{RF2,1}$	2nd Adjacent Channel Transmit Power 2 MHz (1 Mbps)		-54.0		dBc
$P_{RF1,2}$	1st Adjacent Channel Transmit Power 2 MHz (2 Mbps)		-25		dBc
$P_{RF2,2}$	2nd Adjacent Channel Transmit Power 4 MHz (2 Mbps)		-54.0		dBc
E_{em}	Error vector magnitude IEEE 802.15.4		8		%rms
$P_{harm2nd,\ IEEE\ 802.15.4}$	2nd harmonics in IEEE 802.15.4 mode		-51.0		dBm
$P_{harm3rd,\ IEEE\ 802.15.4}$	3rd harmonics in IEEE 802.15.4		-48.0		dBm

6.20.15.5 Receiver operation

Datasheet source: https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf

Symbol	Description	Min.	Typ.	Max.	Units
$P_{RX,MAX}$	Maximum received signal strength at < 0.1% PER		0		dBm
$P_{SENS,1M}$	Sensitivity, 1 Mbps nRF mode ideal transmitter[19]		-93		dBm
$P_{SENS,2M}$	Sensitivity, 2 Mbps nRF mode ideal transmitter[19]		-89		dBm
$P_{SENS,LE,1M,BLE}$	Sensitivity, 1 Mbps BLE ideal transmitter, packet length ≤ 37 bytes BER=1E-3[20]		-95		dBm
$P_{SENS,LE,1M,BLE}$	Sensitivity, 1 Mbps BLE ideal transmitter, packet length ≥ 128 bytes BER=1E-4[21]		-94		dBm
$P_{SENS,LE,2M,BLE}$	Sensitivity, 2 Mbps BLE ideal transmitter, packet length ≤ 37 bytes		-92		dBm
$P_{SENS,LE,LR,125K}$	Sensitivity, 125 kbps BLE mode		-103		dBm
$P_{SENS,LE,LR,500K}$	Sensitivity, 500 kbps BLE mode		-99		dBm
$P_{SENS,IEEE\ 802.15.4}$	Sensitivity in IEEE 802.15.4 mode		-100		dBm

DIY Comparisons

Final table

Type	Bluetooth Low Energy				Zigbee	LoRa		WiFi		
Name	Nordic nRF52840				XBee 3 Pro Module	Semtech SX1276		Expressif ESP8266EX		
Data Rate	1 Mbps	2 Mbps	125 kbps	500 kbps	250 kbps	37.5 kbps*	183.1 kbps*	11 Mbps	54 Mbps	72 Mbps
Range (m)	25	18	79	50	3200	58355	3282	111	12	6
Average Power Consumption (mA in Tx Mode)	5				135	90		143		

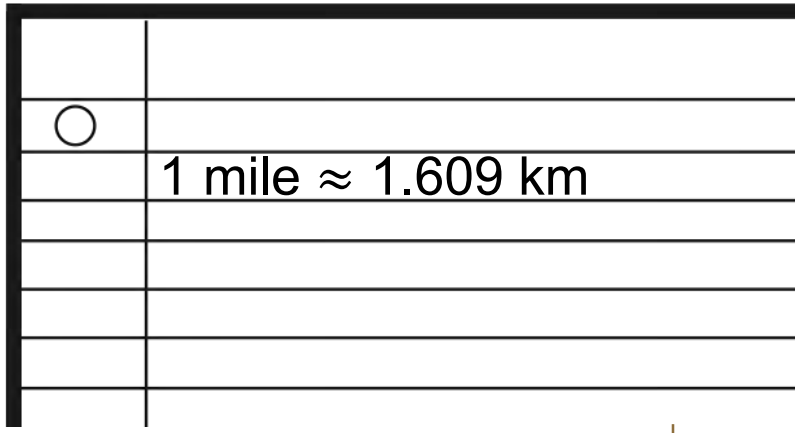
Datasheet specified values Computed values

* Data rate values calculated using Semtech's calculator: https://www.semtech.com/uploads/documents/SX1272LoRaCalculatorSetup1_1.zip

DIY Comparisons

Real-**life scenario "translation"**

I want to test some weather stations in one of my fields. Node data will be uploaded to my gateway device in my farm office 1 mile away once per day and I want the nodes to last at least 4 months on a 1000 mAh battery.



DIY Comparisons

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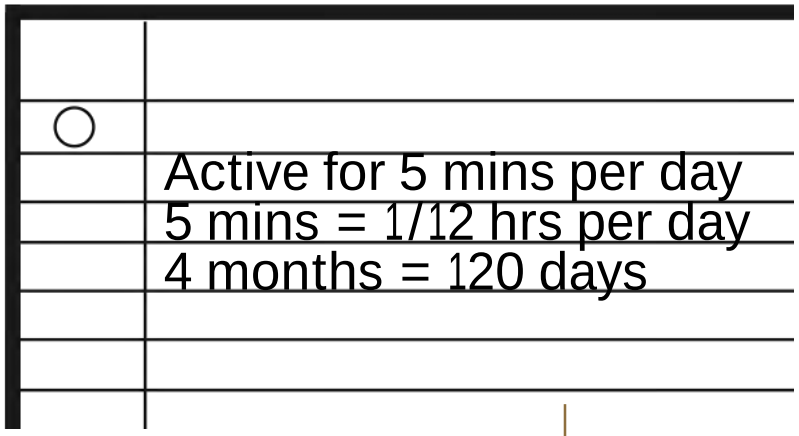

DIY Comparisons

Final table

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Range (m)	25	18	79	50	3200	58355	3282	111	12	6
Average Power Consumption (mA in Tx Mode)	5				143					
				1000 / 135 ≈ 7 hrs		1000 / 90 ≈ 11 hrs				
				7 * 12 = 85 days < 120 days		11 * 12 = 132 days > 120 days				

Datasheet specified values Computed values

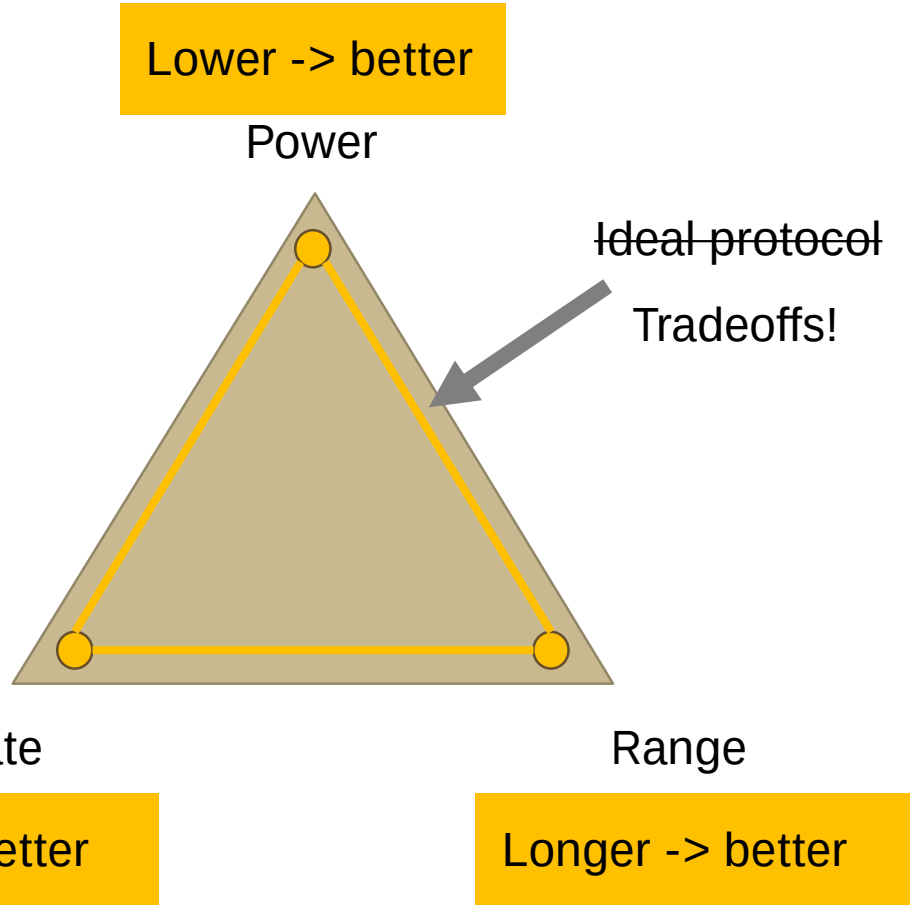
* Data rate values calculated using Semtech's calculator: https://www.semtech.com/uploads/documents/SX1272LoRaCalculatorSetup1_1.zip

Take Home Message

Technical buzzwords can be confusing …

1. Remember the balance triangle
2. Translate your constraints
3. Crawl information and compare

Sometimes no single winner!



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THANK YOU

All questions are welcome! I will try my best to answer them!