

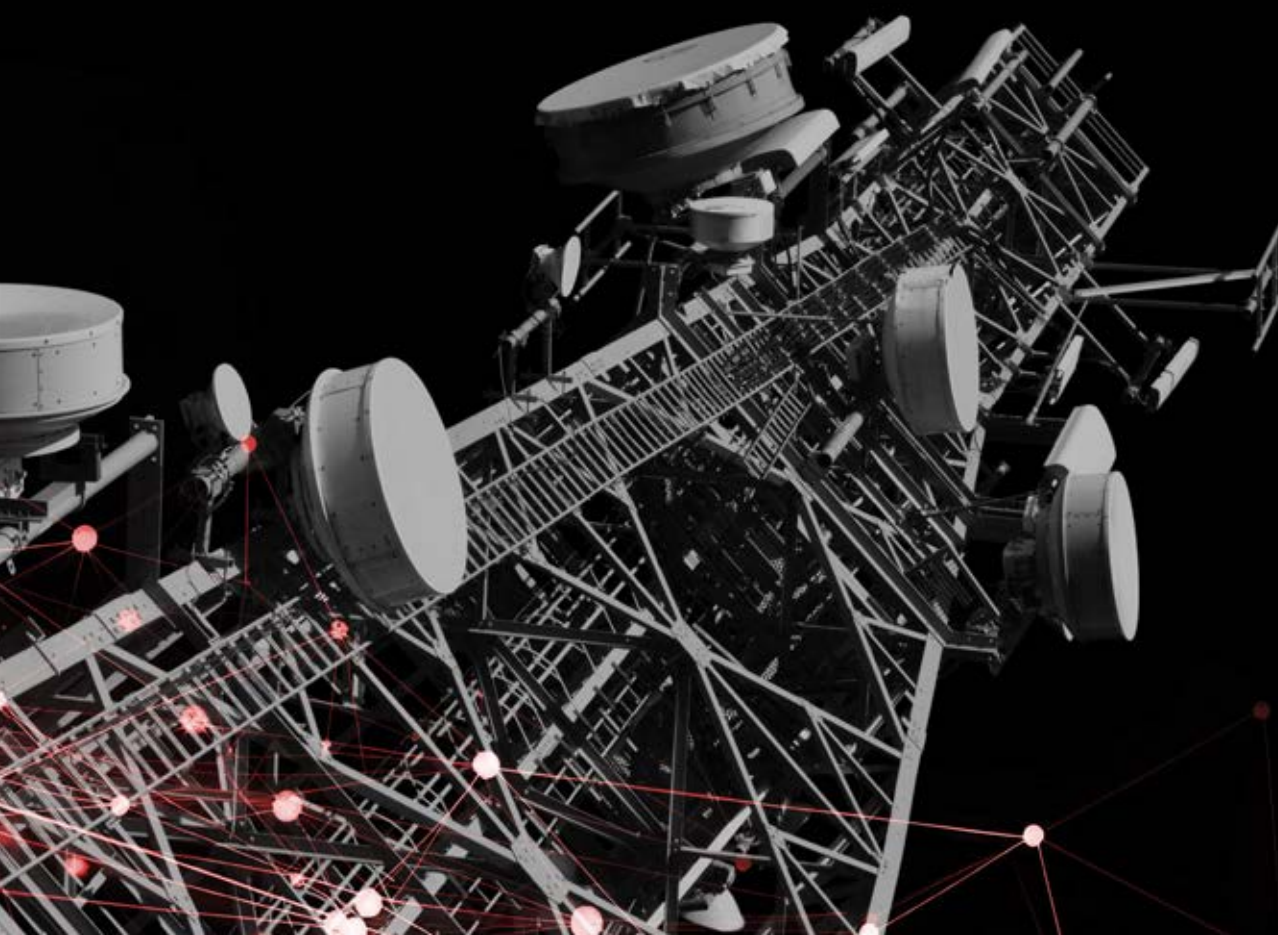
WHITE PAPER

KEY RADIO PARAMETERS FOR SPECTRUM MONITORING RECEIVERS

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Radio receivers for spectrum monitoring are at the heart of spectrum management operations. Therefore, key radio parameters of the receiver, and why they are important, need to be clearly understood, along with minimum recommended values. This allows spectrum managers to specify and select the best radio receiver for a professional spectrum monitoring solution.





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Glossary of terms

TERM	DEFINITION
ADC	Analog to digital converter
GNSS	Global Navigation Satellite System
IBW	Instantaneous bandwidth
IF	Intermediate frequency
IP2	Second-order intercept point
IP3	Third-order intercept point
ISM	Industrial, scientific & medical
LO	Local oscillator
NF	Noise Figure
PN	Phase Noise
POI	Probability of Intercept
RBW	Resolution bandwidth
RF	Radio frequency
RTSA	Real-Time Spectrum Analyzer
SFDR	Spurious free dynamic range
Superhet	Super Heterodyne
UNII	Unlicensed National Information Infrastructure

1. Spectrum monitoring & RF signals

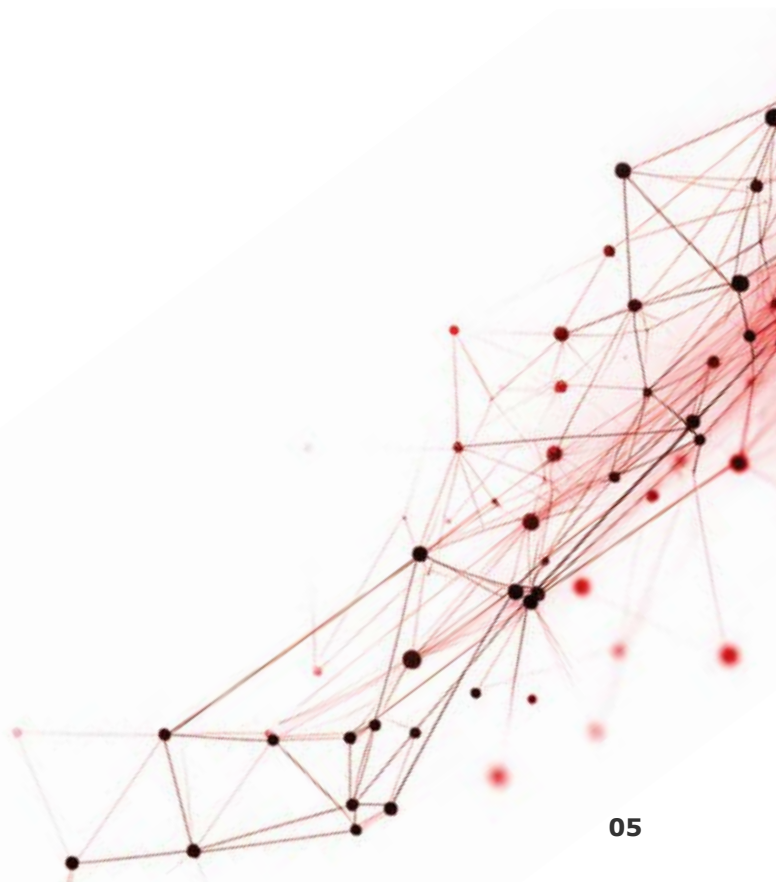
The performance of any spectrum monitoring station or mission is founded upon the RF performance of the spectrum monitoring receivers that are used.

The function of the receiver is to faithfully capture received RF signals via the antenna(s) and provide them as signal measurements to the spectrum monitoring operator. Further processing operations, such as spectral analysis, occupancy measurements, signal intercepts, geolocation, and then demodulation, are all based on these measured signals. It is critical that they are captured with high fidelity and do not suffer any distortion or compromise due to the intrinsic characteristics of the measurement instrument. So far so good—but in reality, it is difficult to capture 100% of all RF signals received with 100% clear fidelity over 100% of the time.

Some challenging scenarios for spectrum monitoring include:

- C1: Distinguishing weak RF signals from the Noise Floor
- C2: Detecting a weak RF signal close in frequency to a much stronger signal
- C3: Detecting short-pulsed signals
- C4: Finding and analyzing transient signals
- C5: Long-term monitoring of spectrum usage and detecting rogue transmitters

For each RF measurement above, the success of the spectrum monitoring mission will rest on how well the receiver performs. This white paper discusses the most critical receiver parameters, details why they are important, and gives guidelines for minimum performance.



2. Key receiver parameters

Key receiver parameters can be broadly categorized into:

- (a) Frequency performance – span of frequencies covered, frequency resolution and accuracy
- (b) POI (Probability of Intercept) – ability to capture short pulses, rare bursts, transients
- (c) Sensitivity – ability to detect weak signals close to the noise floor
- (d) Selectivity – ability to distinguish a weak signal close to a strong signal

The following key parameters (amongst others) are critical in determining the performance of a spectrum monitoring receiver:

Ref	Key Parameter	Category
KP1	Receiver Architecture	Receiver Architecture
KP2	Pre-selection filters	Selectivity
KP3	Frequency Range	Frequency performance
KP4	Frequency accuracy	Frequency performance
KP5	Instantaneous Bandwidth (IBW)	POI
KP6	Sweep Rate	POI
KP7	Noise Figure (NF)	Sensitivity
KP8	Phase Noise (PN)	Selectivity
KP9	Spurious Free Dynamic Range (SFDR)	Selectivity
KP10	Dynamic Range	Selectivity

Each of these parameters will be discussed in detail, but the receiver architecture will ultimately determine the limit of what is achievable in most cases.

2.1 RECEIVER ARCHITECTURE

For spectrum monitoring receivers, the following main choices for receiver architecture are available: Direct conversion, Direct RF sampling, and superheterodyne (superhet).

- (a) Direct conversion (homodyne) receivers convert the RF signal to a zero-Hz signal with a single mixer stage. The advantages are that it is low-cost and simple to implement into an integrated circuit. The main disadvantage is the lower signal fidelity, partly due to DC offsets from local oscillator (LO) leakage. These receivers also suffer from limited image rejection performance (usually 30 – 50 dB without calibration, which can be improved to 50 – 70 dB with calibration). However, this quickly degrades with temperature, and frequent re-calibrations are required.
- (b) Direct RF sampling receivers simply digitize the entire RF signal bandwidth, using modern high-speed ADCs to cover the entire spectrum. The advantage is that the receiver is very simple to implement, and all RF signals are captured. Disadvantages include high noise floor due to very wide noise-equivalent bandwidth, poor dynamic range, and the upper RF frequency being limited by the sampling rate of the digitizer. These receivers are expensive and have relatively poor SFDR.
- (c) Superhet receivers mix the RF signal down to a lower IF frequency, which can then be filtered and sampled as desired. The advantages are a low noise figure, the best selectivity, and the widest frequency range of all the receiver types. This premium RF performance comes at the cost of a larger, more expensive radio receiver overall.

2.2 PRE-SELECTION FILTERS

The design of the receiver front-end to include pre-selection filters depends partly on the receiver architecture (as in Section 2.1). A bank of pre-selection filters at the front end is critical for applications where strong signals may be present in parts of the spectrum, which will de-sensitize the receiver to low-level signals at other frequencies (e.g., powerful signals from a TV or radio broadcast tower, or cellular base station located nearby). By automatically switching between different filter banks during a spectrum sweep, out-of-band signals can then be excluded from the measurement.



2.3 FREQUENCY RANGE

The frequency bands and designators from 1 GHz to 40 GHz are shown below:

Band	Frequency Range	Wavelength Range
L	1 to 2 GHz	15 cm to 30 cm
S	2 to 4 GHz	7.5 cm to 15 cm
C	4 to 8 GHz	3.75 cm to 7.5 cm
X	8 to 12 GHz	25 mm to 37 mm
Ku	12 to 18 GHz	16.7 mm to 25 mm
K	18 to 26.5 GHz	11.3 mm to 16.7 mm
Ka	26.5 to 40 GHz	5.0 mm to 11.3 mm

For spectrum monitoring and management operations, the frequency range needed will depend on the specific application: it may range from as low as 9kHz at the lower limit right up to 3 / 6 / 8 / 18 / 40 GHz at the upper limit. Demand for broadband connectivity is growing continually, and this generally results in a wider and wider frequency range being needed as spectrum at both the upper and lower limits is opened-up. In general, the upper frequency limit is being continually extended because the primary growth driver is for more bandwidth and densification of users, which is ideally suited to higher and higher frequency bands that can provide wider bandwidth and shorter frequency re-use distances.

Traditional spectrum monitoring for regulatory agencies focused on public broadcast frequency bands, which ranged from something like 10MHz at the lower limit up to a few hundred MHz. Public take-up of mobile radio and cellular services initially began in the bands from 400MHz up to 900MHz in the 1990s, and as demand increased this extended in frequency up to 1800MHz. The ISM bands at 2.4GHz being used for Wi-Fi from around 2000 and the 5GHz bands (UNII bands 1 / 2 / 3) subsequently opening required regulators to monitor frequencies as high as 6GHz.

Frequencies above 6GHz were traditionally used for microwave point-to-point links, requiring frequency coordination and individual licensing, but monitoring was not typically required. The UNII bands are now being extended beyond 6GHz for Wi-Fi-6E as far up as the 7GHz band (UNII bands 5 / 6 / 7 / 8), which means that spectrum monitoring receivers need to extend up to at least 8GHz to cover these bands. For cellular services, LTE pushed-up from 2.5GHz into the 3.5GHz band, and 5G now has FR2 with bands up into the 30GHz ranges.

For a spectrum monitoring receiver to provide coverage of at least the public Wi-Fi bands, it is now essential for the upper frequency to extend beyond the 6GHz limit to at least 8GHz. The graphic in Figure 1 shows how the upper frequency has increased for the Wi-Fi bands. In a similar way, 5G bands are increasing both in bandwidth and center frequency; see Figure 2, which provides a snapshot of the 5G bands in December 2020. These will undoubtedly be expanded in coming years, with a consequent requirement for wider-bandwidth spectrum monitoring receivers. Frequencies from 8 GHz up to 40 GHz are becoming ever more widely used. The common usages by band are:

>> **X-band** is useful for radar applications as it has short wavelength, allowing higher resolution imaging for target identification and discrimination. It is used for civil, military, and government radar applications including weather monitoring, air traffic control, maritime vessel traffic control, defense tracking, and vehicle speed detection for law enforcement. X-Band is also used for satellite and terrestrial communications. The frequency range from 8.175 to 8.215 GHz is usually used by meteorological satellites for monitoring weather conditions. The ITU has also allocated 10 to 10.5 GHz for amateur radio operations and 10.45 to 10.5 GHz for amateur satellite operations.

>> **Ku-band** is mostly used for satellite TV and for VSAT systems on ships. Fixed Satellite Service (FSS) (11.7 to 12.7 GHz) and Direct Broadcast Satellite (DBS) (12.2 to 12.7 GHz).

>> **K-band** is used for satellite communications, astronomical observations, and radars. Radars in this frequency range provide short range, high resolution, and high throughput.

>> **Ka-band** is mainly used for satellite communications, and increasingly for mmwave 5G, as shown in Figure 2. The uplink frequency for satellite communications is usually around 27.5 GHz or 31 GHz. Ka-band has several advantages like wide bandwidth, which is double that of the Ku-band and five times more than the C-band. This band has smaller wavelength, which means smaller components leading to smaller antennas and systems; it also gives very high-resolution: best suited for close-range radars.

In summary, it is critically important that the radio receiver is capable of covering the entire frequency range of interest, as higher and higher frequencies are now coming into widespread use for many different applications.

2.4 GHz band Total 80MHz	ISM 80MHz	
	2410	2490

5 GHz band Total 500MHz	UNII-1 80MHz		UNII-2a 80MHz		UNII-2c 240MHz		UNII-3 100MHz	
	5170	5250	5250	5330	5490	5730	5735	5835

6 GHz band Total 1200MHz	UNII-5 500MHz				UNII-6 100MHz		UNII-7 350MHz		UNII-8 250MHz	
	5925			6425	6425	6525	6525	6525	6875	6875 7125



5G frequency bands (as at Dec 2020)

	< 1 GHz	2 GHz	3 GHz	4 GHz	5-7 GHz	24-28 GHz	37-40 GHz
USA	600 MHz	2.5 GHz	3.6 GHz	3.7-4.2 GHz	5.9-7.1 GHz	24 GHz, 27-28 GHz	37-40 GHz
Canada	600 MHz					27-28 GHz	37-40 GHz
EU	700 MHz		3.4-3.8 GHz		5.9-6.4 GHz	24-27 GHz	
UK	700 MHz		3.4-3.8 GHz			26 GHz	
Germany	700 MHz		3.4-3.8 GHz			26 GHz	
France	700 MHz		3.4-3.8 GHz			26 GHz	
Italy	700 MHz		3.6-3.8 GHz			26 GHz	
China			3.3-3.6 GHz	4.8-5 GHz		24-27 GHz	37.5-42 GHz
S. Korea			3.4-3.7 GHz			26-29 GHz	
Japan			3.6-4.2 GHz	4.4-4.9 GHz		27-29 GHz	
Australia			3.4-3.7 GHz			24-27 GHz	39 GHz

2.4 FREQUENCY ACCURACY

The frequency accuracy of the receiver is very important for spectrum monitoring applications, to determine whether or not a particular signal is on its licensed frequency: this is critical for interference protection between multiple users of the spectrum. Frequency accuracy is set by the performance of the frequency synthesizer, which derives its reference from a crystal oscillator disciplined by a GNSS module. An initial accuracy of ± 0.1 ppm would typically be specified in order to provide sufficient performance.

2.5 INSTANTANEOUS BANDWIDTH (IBW)

Modern real-time spectrum analyzers (RTSAs) sample the RF signal digitally, and then perform overlapping FFTs to transform the measurements into a spectrogram. The instantaneous bandwidth (IBW) is set by the ADC sampling frequency and defines the widest bandwidth signal which can be captured at any given center frequency. The IBW affects Probability of Intercept (POI) in two ways:

1. The IBW is the widest bandwidth signal which can be captured with gapless I/Q recording, to give POI of 100%. For example, Wi-Fi channels were originally only 5MHz wide in the 2.4GHz band, which would only have required a receiver with 5MHz IBW to capture the full-rate IQ data. Today's new Wi-Fi channels in the 5GHz and 6GHz bands use wider channels of size 20MHz, 40MHz, 80MHz, and even 160MHz (although 160MHz is typically limited to indoor use only). This means that radio receivers with IBW smaller than the signal bandwidth are unable to capture the full-rate I/Q data to reconstruct the original signal.

2. If a band wider than the receiver IBW is to be monitored, then the receiver will need to sweep, using steps of capture => re-tune => capture => re-tune until the whole band is covered. Figure 3 shows the number of times that a radio receiver would need to step through the capture => re-tune process, in order to monitor the various Wi-Fi bands in Europe and USA. For traditional 2.4GHz ISM bands it

was possible to cover the whole band with IBW of only 20MHz or 40MHz and just a few capture => re-tune cycles. With the new wider 6GHz bands opening-up, the number of re-tunes needed to span the band has increased tenfold or more. Therefore, a receiver with IBW lower than 40MHz will take a relatively long time to sweep the whole band, and will consequently suffer degraded POI. For this reason, an IBW of 40MHz minimum (but preferably 100MHz) is recommended for spectrum monitoring receivers. The number of re-tune cycles to cover a given frequency range also affects the overall sweep rate.

The number of "capture => re-tune" steps needed to cover various Wi-Fi frequency bands by RFeye Nodes

Traditional ISM bands					
Re-tunes		2.4 GHz		5 GHz	
	Freq (MHz)	2400-2500		5725-5875	
	BW (MHz)	100		150	
	Node 40-8	2		3	
	Node 50-8				
	Node 100-8	0		1	

		New European regulations							
		2.4 GHz			5 GHz lower	5 GHz upper	5.9 GHz	6 GHz	
		Freq (MHz)	2400-2500			5170-5330	5470-5700	5850-5925	5925-6425
		BW (MHz)	100			160	230	75	500
Re-tunes		Node 40-8	2			3	5	1	12
		Node 50-8	1			3	4	1	9
		Node 100-8	0			1	2	0	4

		New USA regulations							
		2.4 GHz	3.6 GHz	CBRS	4.9 GHz	5 GHz lower	5 GHz upper	5.9 GHz	6 GHz
Freq (MHz)		2400-2500	3655-3695	3550-3700	4940-4990	5150-5350	5470-5850	5850-5925	5925-7125
BW (MHz)		100	40	150	50	200	380	75	1200
Re-tunes	Node 40-8	2	0	3	1	4	9	1	29
	Node 50-8	1	0	2	0	3	7	1	23
	Node 100-8	0	0	1	0	1	3	0	11

2.6 SWEEP RATE

High sweep rate is important in keeping the POI as high as possible, so that short-burst signals in one part of the spectrum are not missed when the receiver is sweeping another part of the spectrum. Sweep rate depends on synthesizer settling time and IBW and is measured according to ITU-R SM.1839. Sweep rate also depends on the Resolution Bandwidth (RBW) due to the need to integrate for longer time periods when RBW is very small.

For receivers covering wider frequency ranges up to 8GHz or 18GHz, it becomes increasingly important that the sweep rate should be as high as can be achieved. A sweep rate exceeding 100GHz/s for RBW of 2MHz is considered the minimum recommended sweep speed for a span of 8GHz to catch short-burst signals. For frequency spans up to 18GHz, a sweep rate exceeding 300GHz/s is recommended.

2.7 NOISE FIGURE (NF)

Receiver sensitivity is primarily expressed by the Noise Figure (NF), which should ideally be as low as possible. The NF is self-generated noise of the receiver, and is dominated by noise in the input circuitry, which is why there is generally a low noise amplifier (LNA) as close to the receiver front-end as possible. Design of the mixer circuitry is also critical for low NF. NF is measured according to ITU-R SM.1838 and generally increases with increasing frequency. NF less than 12 dB is recommended for receivers spanning up to 8GHz.

2.8 PHASE NOISE (PN)

Receiver phase noise (PN) determines the receiver's ability to resolve two closely spaced signals. Phase noise introduces a "skirt" of noise around the measurement of each signal, and if another signal is close enough in frequency to lie within the skirt, then its measurement will be degraded.

PN is multiplicative and specified as noise density relative to the carrier, at a given offset and measurement frequency, requiring a table of values to describe it. A typical recommendation is that phase noise measured at 1GHz carrier frequency should be less than -115 dBc/Hz at 10kHz offset.

2.9 SPURIOUS FREE DYNAMIC RANGE (SFDR)

SFDR is the ratio of the wanted carrier signal to the strongest self-generated spurious signal of the receiver itself. Low-quality receivers may have a whole forest of self-generated spurious signals throughout the spectrum, which cannot be distinguished from real signals to be measured. Therefore, the SFDR is a critical measure of receiver performance: it is a compound measure of a number of other parameters including NF, IP2, IP3 and known spurious signals such as LO breakthrough. A recommended value for SFDR is 60dBc minimum, measured within the full IBW span of the receiver, across all frequencies.

2.10 DYNAMIC RANGE

Dynamic range defines how well the receiver can measure weak signals in the presence of much stronger adjacent signals. It is influenced by a number of factors, including receiver linearity and gain control range.

(a) Linearity defines the range over which the receiver faithfully reproduces input signals without distortion or compression (output power is linearly dependent on signal input power) and is measured by a number of intercept points, including IP2 and IP3. Once the components of the receiver front-end begin to saturate, intermodulation (IM) products will be introduced, which grow as the input is driven harder. If extrapolated far enough with increasing input signal power, a point will be reached where the second-order IM products will intersect the level of wanted signal. This is known as the IP2 level, and the IP3 level for the third order IM products. Clearly, the higher the IP2 and IP3, the more tolerant the receiver to strong adjacent signals, which is critical for a spectrum monitoring

receiver. IP2 and IP3 are measured according to ITU-R SM.1837, with a recommended value for IP3 of 10dBm or higher above 30MHz.

(b) Gain control range is governed by the gain stages of amplifiers and attenuators, which are electronically inserted / removed from the receive chain by the automatic gain control (AGC). A gain control range of at least 70dB is recommended for the RF receive chain, with additional gain control implemented digitally at baseband.

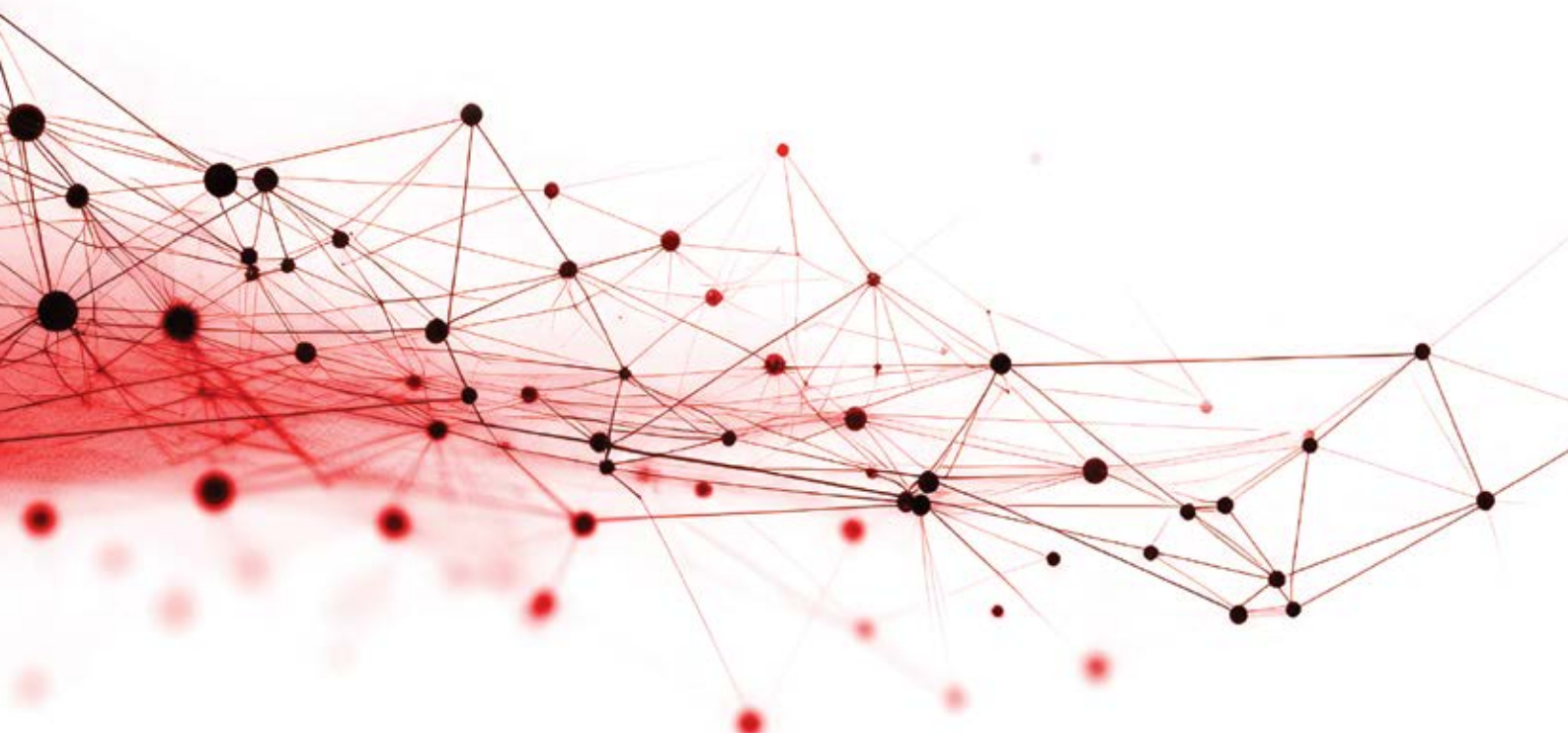
3. Summary

This white paper outlined some of the most critical key parameters for the radio receiver in a spectrum monitoring system. By understanding and carefully considering the effects of these parameters, spectrum managers will be able to specify the most appropriate receiver for their application. RFeye Nodes are designed to give the highest performance according to these and other key parameters.

4. Appendix

Specification of the RFeye Node 100-8 and Node 100-18:

Ref	Key Parameter	RFeye Node 100-8	RFeye Node 100-18
KP1	Receiver Architecture	Super Heterodyne	Super Heterodyne
KP2	Pre-selection filters	12 preselector filters	12 preselector filters
KP3	Frequency Range	9 kHz – 8 GHz	9 kHz – 18 GHz
KP4	Frequency accuracy	±0.1 ppm typ.	±0.1 ppm typ.
KP5	Instantaneous Bandwidth (IBW)	100 MHz	100 MHz
KP6	Sweep Rate	280 GHz/s @ 2MHz RBW	390 GHz/s @ 2MHz RBW
KP7	Noise Figure (NF)	6 dB to 10 dB	7 dB to 21 dB
KP8	Phase Noise (PN)	130 dBc/Hz at 20 kHz offset @ 1GHz input	126 dBc/Hz at 20 kHz offset @ 1GHz input
KP9	Spurious Free Dynamic Range (SFDR)	75 dB typ.	75 dB to 80 dB typ.
KP10	Dynamic Range	77 dB to 82 dB gain control range	80 dB gain control range



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