Speedway® Revolution Reader Application Note

Low Level User Data Support

This application note provides the operator of a Speedway Revolution reader with the necessary information to utilize the Radio Frequency (RF) phase and Received Signal Strength Indication (RSSI) low level user data.

The target audience is any party interested in using the RF phase and RSSI reporting features.

Note that the low level user data feature requires a Speedway Revolution reader with at least Octane 4.4 firmware to receive any low level tag metrics, however the latest optimizations to these tag reports, including the Doppler effects described here, are available beginning with Octane 4.8.

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1 Introduction

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1.1 Terminology

Table 1-1 provides a listing of terminology used within this document.

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Hz	Hertz is an SI unit of frequency (1 Hz = 1 cycle/second)
LLRP	Low Level Reader Protocol
Radial	Along a vector connecting the reader antenna to the tag
Isotropic	Identical in all directions; invariant with respect to direction.
Multipath Propagation	Electromagnetic wavefronts from the same transmission source reaching a receiving antenna through two or more paths.
RCS	Radar Cross Section
RF	Radio Frequency
RFID	Radio Frequency IDentification
RSSI	Receive Signal Strength Indication
SNR	Signal to Noise Ratio
UHF	Ultra High Frequency
Watts	Watt is an SI unit of power (1 Watt = 1 Joule/second)

2 Configuration

When loaded with the Octane 4.4, or newer versions of software, the Speedway Revolution reader supports RF phase and RSSI reporting through custom extensions of the Low Level Reader Protocol (LLRP). The **ImpinjTagReportContentSelector** parameter allows the operator to configure additional parameters to be reported via the **TagReportData** parameter including the **ImpinjRFPhaseAngle**, **ImpinjPeakRSSI** and **ImpinjRFDoppler** parameters. For a complete description of how to enable the low level user data feature for the Speedway Revolution reader please refer to the Octane LLRP Version 4.8 documentation.

2.1 Example LLRP ROSpec

The following is an example ROSpec that includes the **ImpinjTagReportContentSelector** parameter with the **ImpinjRFPhaseAngle**, **ImpinjPeakRSSI** and **ImpinjRFDoppler** parameters enabled.

```
<?xml version="1.0"?>
<llrp:ADD_ROSPEC Version="1" MessageID="0"
 xmlns:llrp="http://www.llrp.org/ltk/schema/core/encoding/xml/1.0"
 xmlns:Impinj="http://developer.impinj.com/ltk/schema/encoding/xml/1.8">
 <llrp:ROSpec>
  <llrp:ROSpecID>1</llrp:ROSpecID>
  <llrp:Priority>0</llrp:Priority>
  <llrp:CurrentState>Disabled</llrp:CurrentState>
  <llrp:ROBoundarySpec>
   <llrp:ROSpecStartTrigger>
    <llrp:ROSpecStartTriggerType>Null</llrp:ROSpecStartTriggerType>
   </llrp:ROSpecStartTrigger>
   <llrp:ROSpecStopTrigger>
    <llrp:ROSpecStopTriggerType>Null</llrp:ROSpecStopTriggerType>
    <llrp:DurationTriggerValue>0</llrp:DurationTriggerValue>
```

```
    </llrp:ROSpecStopTrigger>

  </llrp:ROBoundarySpec>

  <llrp:AISpec>

    <llrp:AntennaIDs>0</llrp:AntennaIDs>

    <llrp:AISpecStopTrigger>

      <llrp:AISpecStopTriggerType>Null</llrp:AISpecStopTriggerType>

      <llrp:DurationTrigger>0</llrp:DurationTrigger>

    </llrp:AISpecStopTrigger>

    <llrp:InventoryParameterSpec>

      <llrp:InventoryParameterSpecID>1</llrp:InventoryParameterSpecID>

      <llrp:ProtocolID>EPCGlobalClass1Gen2</llrp:ProtocolID>

    </llrp:InventoryParameterSpec>

  </llrp:AISpec>

  <llrp:ROReportSpec>

    <llrp:ROReportTrigger>Upon_N_Tags_Or_End_Of_ROSpec</llrp:ROReportTrigger>

    <llrp:N>1</llrp:N>

    <llrp:TagReportContentSelector>

      <llrp:EnableROSpecID>false</llrp:EnableROSpecID>

      <llrp:EnableSpecIndex>false</llrp:EnableSpecIndex>

      <llrp:EnableInventoryParameterSpecID>false</llrp:EnableInventoryParameterSpecID>

      <llrp:EnableAntennaID>false</llrp:EnableAntennaID>

      <llrp:EnableChannelIndex>false</llrp:EnableChannelIndex>

      <llrp:EnablePeakRSSI>false</llrp:EnablePeakRSSI>

      <llrp:EnableFirstSeenTimestamp>false</llrp:EnableFirstSeenTimestamp>

      <llrp:EnableLastSeenTimestamp>false</llrp:EnableLastSeenTimestamp>
```

```
    <llrp:EnableTagSeenCount>false</llrp:EnableTagSeenCount>
    <llrp:EnableAccessSpecID>false</llrp:EnableAccessSpecID>
    <llrp:C1G2EPCMemorySelector>
     <llrp:EnableCRC>false</llrp:EnableCRC>
     <llrp:EnablePCBits>false</llrp:EnablePCBits>
    </llrp:C1G2EPCMemorySelector>
   </llrp:TagReportContentSelector>
   <Impinj:ImpinjTagReportContentSelector>
    <Impinj:ImpinjEnableSerializedTID>false</Impinj:ImpinjEnableSerializedTID>
    <Impinj:ImpinjEnableRFPhaseAngle>true</Impinj:ImpinjEnableRFPhaseAngle>
    <Impinj:ImpinjEnablePeakRSSI>true</Impinj:ImpinjEnablePeakRSSI>
    <Impinj:ImpinjEnableRFDopplerFrequency>true</Impinj:ImpinjEnableRFDopplerFrequency>
   </Impinj:ImpinjTagReportContentSelector>
  </llrp:ROReportSpec>
 </llrp:ROSpec>
</llrp:ADD_ROSPEC>
```

Figure 2-1: Sample LLRP ROSpec

2.2 Example RO_ACCESS_REPORT

The following example RO_ACCESS_REPORT illustrates the reported RF phase and the RSSI values. The RF phase parameter is a 12-bit value that can be converted to degrees as

$$768 \cdot \frac{360}{4096} = 67.5^\circ \text{, or to radians as } 768 \cdot \frac{2\pi}{4096} = 1.18 \text{ rad.}$$

The Impinj Peak RSSI is reported in dBm x 100 so a reported value of -4050 = -40.50 dBm. For a complete description of RF phase and RSSI formatting, please refer to Sections 3.1.3 and 3.2.4 of this document.

```
?xml version="1.0"?>
RO_ACCESS_REPORT  Version="1" MessageID="909784410"
xmlns:llrp="http://www.llrp.org/ltk/schema/core/encoding/xml/1.0"
xmlns:Impinj="http://developer.impinj.com/ltk/schema/encoding/xml/1.8">
<TagReportData>
  <EPCData>
    <EPC Count="128">99997777777755555555333333330000</EPC>
  </EPCData>
  <Impinj:ImpinjRFPhaseAngle>
    <Impinj:PhaseAngle>768</Impinj:PhaseAngle>
  </Impinj:ImpinjRFPhaseAngle>
  <Impinj:ImpinjPeakRSSI>
    <Impinj:RSSI>-4050</Impinj:RSSI>
  </Impinj:ImpinjPeakRSSI>
  <Impinj:ImpinjRFDopplerFrequency>
    <Impinj: DopplerFrequency>87</Impinj: DopplerFrequency>
  </Impinj:ImpinjRFDopplerFrequency>
</TagReportData>
/RO_ACCESS_REPORT> <?xml version="1.0" ?>
```

Figure 2-2: Example of LLRP RO_ACCESS_REPORT

3 Low Level User Data

This application note provides a cursory introduction to those radio propagation topics immediately relevant to the Speedway Revolution reader RSSI and RF phase user data. A comprehensive description of radar techniques and electromagnetic wave propagation are beyond the scope of this paper. The operator is encouraged to reference one of the many texts available on those subjects.

3.1 Backscatter Power

3.1.1 Theory

Figure 3-1 provides a conceptual diagram of the radio wave propagation between an RFID reader and a passive RFID tag.

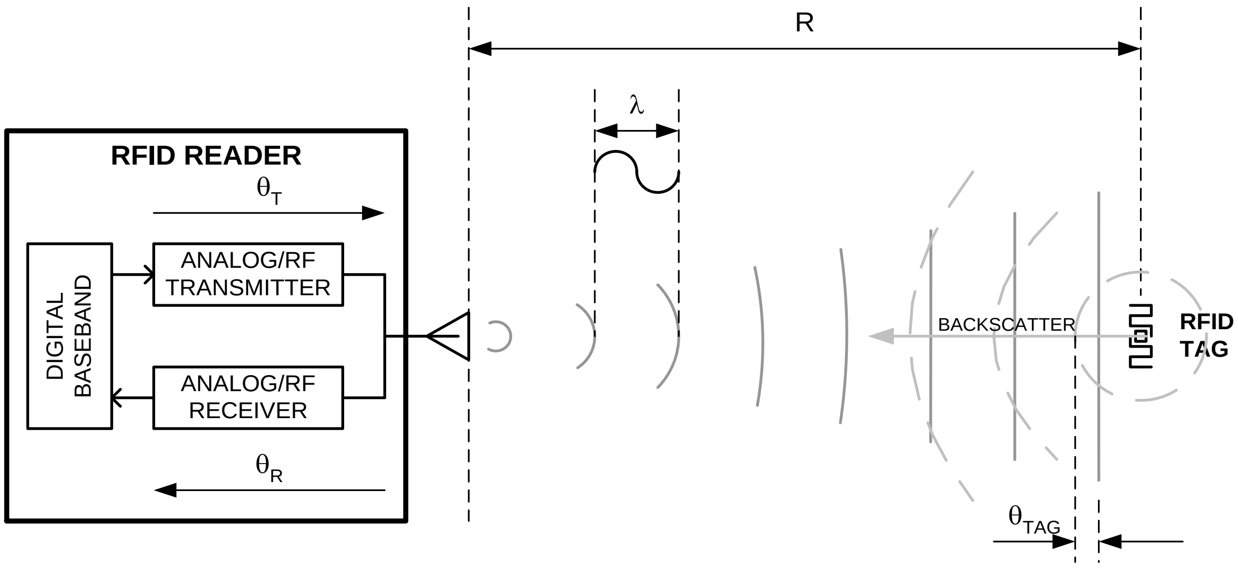

Figure 3-1: Conceptual diagram of radio wave propagation between RFID reader and tag

The two-way radar equation for a monostatic transmitter, Equation 3-1, provides an estimate of the tag backscatter signal power received (P_R) by an RFID reader as a function of the following parameters:

P_T = Reader transmit power at the transmit antenna input (Watts)

G_T = Reader antenna gain

λ = Carrier wavelength (meters)

σ = Tag Radar Cross Section (meters^2)

R = Distance between reader and tag (meters)

$$P_R = \frac{G_T^2 \cdot \lambda^2 \cdot \sigma}{(4 \cdot \pi)^3 \cdot R^4} \cdot P_T \text{ (Watts)}$$

Equation 3-1

The two-way radar equation is a form of the well-known Friis equation applied to both directions of the radar link (reader-to-tag and tag-to-reader). The receiver antenna gain term (G_R) in the standard Friis equation is replaced by a factor comprehending the target's Radar Cross Section (RCS), $G_R = 4\pi\sigma/\lambda^2$. An object's RCS is a measure of the effective area for capturing incident energy and isotropically scattering it back to the source. The RCS for a passive RFID tag depends on antenna design, impedance matching, and the changes in reflection coefficient as a function of tag modulator state.

The received signal power decays as $1/R^4$ due to the product of the two free-space loss factors, $1/R^2$, for each link direction (reader-to-tag and tag-to-reader).

3.1.2 Environmental and Other Effects

Many factors can affect the received power, causing it to be different than predicted by the two-way radar equation. Propagation effects such as absorption and scattering as well as antenna effects such as impedance mismatch and polarization mismatch can reduce the power observed at the reader receiver. Multipath propagation and undesired signals in the environment can combine with the primary backscatter, thereby increasing or decreasing the received signal power at the reader receiver.

3.1.3 Speedway Revolution Reader RSSI Reporting

The RSSI reported by the Speedway Revolution reader is a power measurement taken within the channel filter bandwidth and reported as a 16-bit signed value in units of dBm x 100. Table 3-1 provides an overview of the Speedway Revolution reader RSSI reporting capabilities.

Table 3-1: RSSI Reporting Parameters

Description	Min	Typ	Max	Units	Comments/Conditions
RSSI Word Size		16		Bits	Twos complement
RSSI Range	-110		0	dBm	Reporting range only. Reader measurement capability limited to approximately -90 dBm.
RSSI Resolution	0.5			dB	
RSSI Standard Deviation			1	dB	Standard deviation from mean value over 1000 EPC packets in an anechoic chamber or a cabled test. 0 to +40 ºC Absolute accuracy of mean value is not specified.

3.2 RF Phase

3.2.1 Theory

For an RF carrier wave at frequency *f* (Hz), the relation between frequency and wavelength is given by

$$\lambda = \frac{c}{f} \text{ (meters)}$$

Equation 3-2

where *c* is the speed of the EM wave in the communication medium which, in air, is equal to the speed of light (3 × 10^8 m/s).

As shown in Figure 3-1, the total distance traversed by the signal will be 2R. In addition to the RF phase rotation over distance, the reader's transmit circuits, the tag's reflection characteristic, and the reader's receiver circuits will all introduce some additional phase rotation θ_T, θ_{TAG}, and θ_R respectively. The total phase rotation can be expressed as

$$\theta = 2 \cdot \pi \cdot \left(\frac{2R}{\lambda} \right) + \theta_T + \theta_R + \theta_{TAG}$$

Equation 3-3

Since phase is a periodic function with period 2π radians, the phase values will clearly repeat at distances separated by integer multiples of one-half the carrier wavelength

$$R_n = \frac{n\lambda}{2} \text{ , n = 0,1,2, …}$$

Equation 3-4

3.2.2 Environmental and Other Effects

A reader might employ open-loop estimation techniques such as preamble correlation or closed-loop estimation for acquiring and/or tracking carrier phase. In all cases the phase estimate must be derived from the received signal and the estimate will be a function of the Signal-to-Noise-Ratio (SNR). The more noise energy within the receiver bandwidth, the greater the phase standard deviation. Thermal noise from the reader receiver is always present but other noise sources, such as external interference, can also affect the reported RF phase.

As mentioned in 3.1.1 the RF phase is a periodic function and will be estimated modulo-2π. In addition, the Speedway Revolution reader receive signal processing introduces π radians of ambiguity such that the reported phase can be the true phase (θ) or the true phase plus π radians ($\theta+\pi$).

3.2.3 Inventory, Antenna Switching, and Frequency Hopping Effects

The Speedway Revolution reader provides one RF phase estimate each time a tag is successfully inventoried. If an application employs multiple samples of the RF phase from a single tag, the application must comprehend the following:

1. Phase estimates should only be compared on a single antenna and channel. RF phase is a function of frequency and antenna path as shown by Equation 3-3.
2. Gen2 UHF RFID employs a slotted-aloha media access scheme, which means that the order in which tags are inventoried will be random. The time between successive inventories of the same tag will depend on reader mode, tag population size, and environmental conditions (e.g. interference levels). Since RF phase is a function of radial distance between reader and tag, the phase difference between successive inventories of the same tag will depend on the elapsed time between the two inventories and the tag's radial velocity.

3.2.4 Speedway Revolution Reader RF Phase Reporting

Table 3-2 provides an overview of the Speedway Revolution reader RF phase reporting capabilities.

Table 3-2: RF Phase Reporting Parameters

Description	Min	Typ	Max	Units	Comments/Conditions
Phase Word Size		12		Bits	Reported value between 0 and 4095
Phase Word Range	0		+2π	Rad	See Figure 3-2 for phase mapping
	0		+360	Deg	
Phase Standard Deviation	-0.1		0.1	Rad	Standard deviation from mean value over 1000 EPC packets in an anechoic chamber or a cabled test. Over 0 to +40 ºC. Over frequency band. Over RSSI from -70 to -30 dBm. Absolute accuracy of mean value is not specified.
	-5.7		5.7	Deg	
Phase Resolution	0.0015			Rad	
	0.088			Deg	

Figure 3-2 diagrams the mapping of phase to the 12-bit value reported by the Speedway Revolution reader.

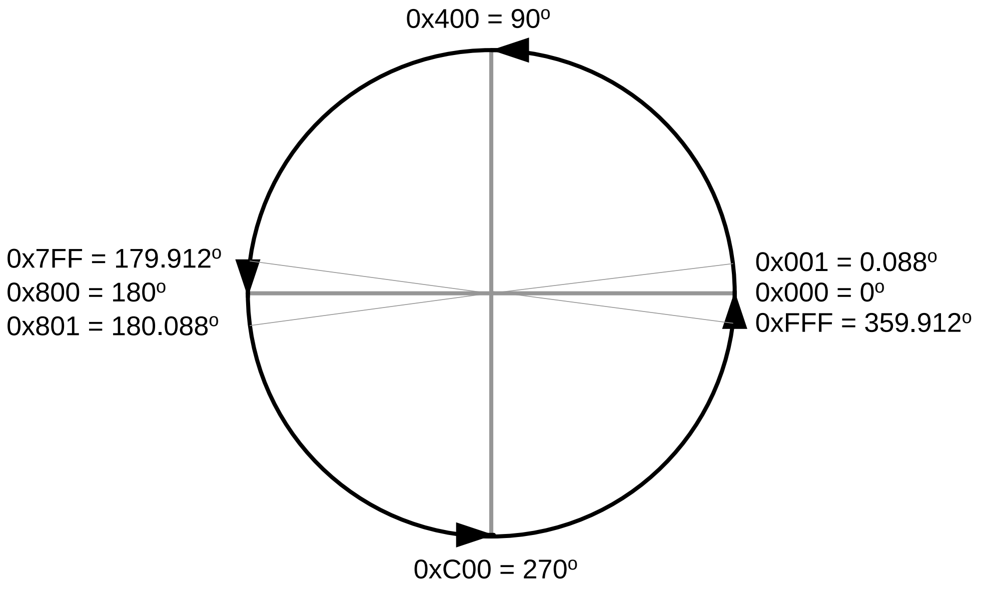

Figure 3-2: Mapping of phase to the 12-bit reported value

3.2.5 Computing Velocity from RF Phase

If two time-phase pairs are measured for the same tag, one at (t_0, θ_0) and one at (t_1, θ_1), the radial distance traversed by the tag is

$$d_{RADIAL} = \frac{1}{2}\left(\frac{\theta_1 - \theta_0}{2^{12}}\right)\cdot\lambda \ \text{(m)}$$

Equation 3-5

Equation 3-5 assumes that the tag moves less than half a wavelength in the radial direction between observations ($d_{RADIAL} < \lambda/2$). The difference in the observation times provides the radial velocity

$$v_{RADIAL} = \frac{d_{RADIAL}}{t_1 - t_0} \ \text{(m/s)}$$

Equation 3-6

The radial direction of travel is given by the sign of the radial velocity v_{RADIAL}.

3.3 Doppler Frequency Shift

When loaded with the Octane 4.8, or newer versions of software, the Speedway Revolution reader supports Doppler frequency shift reporting through custom extensions of the Low Level Reader Protocol (LLRP). This feature is useful for determining tags in motion (i.e. through a portal) versus stationary tags and, in some cases, helping to determine tag directionality.

3.3.1 Theory

Doppler frequency shift is the shift in frequency of the received signal at the reader due to relative motion between the reader and the tag. Assuming the tagged object velocity v is much less than the speed of light, the Doppler frequency shift on a reader carrier signal of wavelength λ is

$$f_m = \frac{2 \cdot v}{\lambda} \cdot \cos(\alpha)$$

Equation 3-7

where α is the angle between the object velocity vector and the reader antenna. The factor of 2 arises from the tag backscattering the reader's carrier signal. Doppler frequency shift is a function of the angle α between the tag's direction of motion and the observing antenna. For example, the Doppler frequency shift goes to zero when the velocity vector is exactly perpendicular to the receiving antenna since the cosine of α=90 degrees (or $\pi/2$ radians) is zero.

Let ΔT denote the time duration of a packet. A Doppler frequency shift of f_m Hz introduces a phase rotation over this packet duration given by

$$\Delta\theta = 2 \cdot \pi \cdot (2 \cdot f_m \cdot \Delta T)$$

Equation 3-8

The Doppler frequency shift experienced by the reader can thus be calculated by measuring the phase rotation across a packet and using the following expression:

$$f_m = \frac{\Delta\theta}{4\pi\Delta T}$$

Equation 3-9

Estimating Doppler frequency shift over the duration of a single packet avoids many of the pitfalls (e.g. stochastic inventory protocol, antenna switching, channel hopping) inherent to using the RF phase from two different packets. Of course, the time aperture of a single packet places limits on the range and accuracy of Doppler frequency shift estimates (refer to Table 3-3).

3.3.2 Speedway Revolution Reader Doppler Frequency Shift Reporting

Table 3-3 provides an overview of the Speedway Revolution reader Doppler frequency shift reporting capabilities.

Table 3-3: Doppler Frequency Shift Reporting Parameters

Description	Min	Typ	Max	Units	Comments/Conditions
Representation	-2^{12}		2^{12}-1	Hz	16-bit (four fractional) Twos complement
Phase Accumulation ($\Delta\theta$)	-720		+720	Deg	Maximum allowed phase accumulation over the duration of any single packet
	-4π		$+4\pi$	Rad	
Frequency Range (f_m)		$\frac{1}{180 \cdot \Delta T} < f_m < \frac{1}{\Delta T}$	Hz		ΔT = packet duration (sec) Lower limit assumes a (arbitrary) minimum of ≈ 4° phase rotation.

The first row in Table 3-3 states the measured value is a 16-bit twos complement number with four fractional bits and units of Hertz. To account for the places to the right of the decimal point the reported Doppler frequency shift value can be converted to Hertz by dividing it by 2^4 or 16. For example, a reported value of 87 for DopplerFrequency in Figure 2-2 would convert to 5.4375 Hz.

The bottom row in Table 3-3 gives a typical range of Doppler frequencies (f_m) that might be reasonably estimated for a given packet duration. For example, if the FCC version of Speedway Revolution reader is configured for LLRP GEN 2 mode ‘3’ operation (Dense Reader, M=8, BLF=170.6kHz) and is receiving a 128-bit packet from the tag, the packet duration is

$$\Delta T = \frac{128\,\text{bits}}{21\text{kHz}} \approx 6\,\text{ms}$$

For these specific DRM settings and EPC length, an estimate of the minimum and maximum Doppler frequency shift that can be measured is (from Table 3-3):

$$\min\left(f_m\right) = \frac{1}{180 \cdot 6\,\text{ms}} \approx 1\,\text{Hz}, \qquad \max\left(f_m\right) = \frac{1}{6\,\text{ms}} \approx 167\,\text{Hz}$$

It should be clear that estimating small Doppler frequency shift requires longer packet durations (e.g. increased EPC length and/or slower reverse link rate). The opposite is obviously true for large Doppler frequency shifts.

Table 3-4: Example Range of Measurable Doppler Frequency Shifts

Reader Hardware	M	BLF (kHz)	Data Rate (bps)	Packet Duration (ms)	Minimum Measurable Doppler Shift (Hz)	Maximum Measurable Doppler Shift (Hz)
FCC	M=8	170.6	21	6	1	167
ETSI	M=8	320	40	3.2	1.7	312

3.3.3 Accuracy of Doppler Frequency Shift Reporting

Table 3-34 provides only a typical range of measurable Doppler frequency shift. Many factors influence the reader's ability to obtain useful Doppler estimates. As described in Subsection 3.2.2, both the minimum detectable Doppler frequency shift and the accuracy of these estimates will depend upon the Signal-to-Noise-Ratio of the received signal. Any increase in noise energy within the receive bandwidth will increase the variance of the measurements. Non line-of-sight (NLOS) signal components due to multipath propagation can also distort the measurement results.

Equation 3-7 clearly shows the dependence on the angle between direction of travel and the reader antenna. As the object moves perpendicular to the reader antenna the Doppler frequency shift decreases and eventually goes to zero as the cosine term goes to zero.

Longer measurement intervals (i.e. longer packet durations) typically provide more accurate Doppler frequency shift estimates. Therefore it is generally desirable to use slower (e.g. M=8) reader inventory modes to measure Doppler frequency shift.

3.3.4 Calculation of Velocity from Doppler Frequency Shift Reporting

Velocity can be estimated from the Doppler frequency shift value by solving Equation 3-7 for the velocity term

$$v = \frac{\hat{f}_m \cdot \lambda}{2 \cdot \cos(\alpha)}$$

Equation 3-10

where $\hat{f}_m$ is the estimated Doppler frequency shift value. The dependence on the angle α between the tag's velocity vector and the reader antenna is again clear in Equation 3-10, which is only valid for α not equal to any multiple of $\pi/2$.

4 Revision History

Date	Revision	Comments
08/12/2010	1.0	Original release
05/26/2011	2.0	Updated for Doppler Frequency in Octane 4.8
07/05/2012	3.0	Expanded Doppler Frequency reporting, section 3.3

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