1 Sub-packets

As shortly explained in document section **??**, data sub-packets are generated depending on its designated data format and length when data reading from each sensor if valid. The first byte of the sub-packet is sensor ID for each parameter, and the second byte means validity of the packet and length of the sensor data as shown in Table **??**. Detail of sub-packet and sensor data will be explined in this section.

1.1 Parameters

The sensor boards output a set of parameters which are identified by a unique ID. Each parameter has a set of values associated with it which are encoded in an appropriate data format. The table below lists the various parameters produced by the sensor boards, the unique source ID used to identify them, the values produced by them and the format in which the value is encoded.

Each parameter and its values are composed into a sub-packet based on the format described in document section **??**. In the case of parameters with 2 or more values, the encoded values are arranged in the sub-packets sequentially.

Table 1: Data sub-packet structure (each row is a "chunk")

Parameter	Source ID	Values	Formats
Firmware version	0xFD	Firmware version (HW/SW)	Bit mask
		Build time	
		Build git	
Airsense board			
Airsense/Lightsense MAC address	0x00	MAC Address	Format 3
TMP112	0x01	Temperature	Format 6
HTU21D	0x02	Temperature	Format 6
		relative humidity	
BMP180	0x04	Temperature	Format 6
		Pressure	Format 4
PR103J2	0x05	Temperature	Format 1
TSL250RD	0x06	Visible Light	Format 1
MMA8452Q	0x07	Acceleration in X	Format 6
		Acceleration in Y	
		Acceleration in Z	
		Vibration	

Table1 – continued from previous page

Parameter	Source ID	Values	Formats
SPV1840LR5H-B	0x08	RMS Sound Level	Format 1
TSYS01	0x09	Temperature	Format 6
Lightsense board			
HMC5883L	0x0A	Magnetic Field in Z	Format 8
		Magnetic Field in Y	
		Magnetic Field in Z	
HIH6130	0x0B	Temperature	Format 6
		relative humidity	
APDS-9006-020	0x0C	Ambient light intensity	Format 1
TSL260RD	0x0D	IR intensity	Format 1
TSL250RD	0x0E	Visible light intensity	Format 1
MLX75305	0x0F	Light	Format 1
ML8511	0x10	UV intensity	Format 1
TMP421	0x13	Temperature	Format 6
SPV1840LR5H-B	0x14	RMS Sound Level	Format 1
Chemsense board			
Total reducing gases	0x15	Raw Concentration	Format 5
Nitrogen dioxide	0x17		
Ozone	0x18		
Hydrogen sulphide	0x19		
Total oxidizing gases	0x1A		
Carbon monoxide	0x1B		
Sulfur dioxide	0x1C		
SHT25	0x1D	Temperature	Format 2
		relative humidity	
LPS25H	0x1E	Temperature	Format 2
		Pressure	Format 4
Si1145	0x1F	UV intensity	Format 1
		Visible light intensity	
		IR intensity	
Chemsense MAC address	0x20	MAC Address	Format 3
CO ADC temp	0x21	ADC temperature	Format 2
IAQ IRR ADC temp	0x22		

Table1 – continued from previous page

Parameter	Source ID	Values	Formats
O3 NO2 ADC temp	0x23	ADC temperature	Format 2
SO2 H2S ADC temp	0x24		
CO LMP temp	0x25		
Accelerometer	0x26	Acceleration in X	Format 2
		Acceleration in Y	
		Acceleration in Z	
		Vibration	Format 4
Gyro	0x27	Orientation in X	Format 2
		Orientation in Y	
		Orientation in Z	
		Orientation Index	Format 4
Alpha Sensor			
Histogram	0x28	Bin count	Raw reading
		Average Time	
		Sample flow rate	
		Temp/Pressure(alther)	
		Sampling period	
		Sum of the counts	
		PM 1	
		PM 2.5	
		PM 10	
Firmware	0x29	Firmware version	
Configuration A	0x30	Bin Boundaries	
		Bin Particle Volumes A	
Configuration B	0x31	Bin Particle Volumes B	
		Bin Particle Densities A	
Configuration C	0x32	Bin Particle Densities B	
		Bin Sample Volume Weightings A	
Configuration D	0x33	Bin Sample Volume Weightings B	
		Gain Scaling Coefficient	
		Sample Flow Rate	
		Laser DAC and Fan DAC	
		Conversion factor	
		Space Bytes	

1.2 Data packets

The context of each parameter, its utility and the arrangement of its values is described below. In all the tables below, the validity bit is set to 1, which means the data is valid. The parameter descriptions below are aggregated based on the sensor-board they are situated on - Metsense, Lightsense and Chemsense.

1.2.1 Firmware Version

This is a 8 bytes version information that identifies hardware version, software version, and build information of the waggle node. The build time and the build git are included to varify the effectiveness of the software. Firmware version is bit masked and encoded through format 1, and build git is encoded through format 1.

0xFD	**0x88**	**Firmware version in Format 1**	**Build time**	**Build git in Format 1**
Byte[0]	Byte[1]	Bytes[2 – 3]	Bytes[4 – 7]	Bytes[8 – 9]

Table 2: Sub-packet of Firmware version

3 bit major HW ver. | 3 bit minor HW ver. | 2 bit major SW ver.	Byte[2]
2 bit major SW ver. | minor SW ver. × 10 + sub SW ver.	Byte[3]

Table 3: Firmware version

2 Sensor Data Units

2.1 Raw and Processed

The sensor boards output a set of values which have various units for the data. The table below lists the various units of sensor values. 'Raw Units' in the table means the unit of the packtized data, which is you can get directly from the packet, and 'Processed Units' means the unit which can be used after data conversion through designated equations. The equations will be provided comming subsections.

Table 4: Sensor units both in raw and processed format

Sensor/Parameter	Raw Units	Processed Units	Comments
Firmware version	No Units		*See appendix A
Airsense board			
Air/Lightsense MAC	No Units	No Units	
TMP112	°C	°C	
HTU21D	°C, %RH	°C, %RH	
BMP180	°C, Pa	°C, Pa	
PR103J2	integer	°C	
TSL250RD	integer	μw/m^2	
MMA8452Q	g, g, g, g	g, g, g, g	
SPV1840LR5H-B	integer		
TSYS01	°C	°C	
Lightsense board			
HMC5883L	G, G, G	G, G, G	
HIH6130	°C, %RH	°C, %RH	
APDS-9006-020	integer	lux	
TSL260RD	integer	μw/m^2	
TSL250RD	integer	μw/m^2	
MLX75305	integer	μw/m^2	
ML8511	integer	UV index	
TMP421	°C	°C	
SPV1840LR5H-B	integer		
Chemsense board			
Total reducing gases	AFE ADC counts		Raw ADC reading
Nitrogen dioxide			

Table 4 – continued from previous page

Sensor/Parameter	Raw Units	Processed Units	Comments
Ozone	AFE ADC counts		Raw ADC reading
Hydrogen sulphide			
Total oxidizing gases			
Carbon monoxide			
Sulfur dioxide			
SHT25	100ths of °C / %RH	°C, %RH	
LPS25H	100ths of °C, Pa	°C, Pa	
Si1145	Three fixed dummy value		Uncompleted FW
Intel MAC address	No Units	No Units	
CO ADC temp	100ths of °C	°C	
IAQ IRR ADC temp			
O3 NO2 ADC temp			
SO2 H2S ADC temp			
CO LMP temp			
Accelerometer	raw register		Raw reading
Gyro			
Alpha sensor			
Histogram			
Bin count	raw integer		
Average time	raw integer		value 10 = 3.33 μs
Sample flow rate	ml/s		
Temp/Pressure(alter)	10ths of °C / Pa (alter)		
Sampling period	raw float		
Sum of the counts	raw integer		
PM1	$\mu g/m^3$		
PM2.5	$\mu g/m^3$		
PM10	$\mu g/m^3$		
Firmware			
Firmware	raw integer		
Configuration			
Configuration Packet A (Source ID 0x30)			
Bin boundaries	raw integer		
Bin particle Volumes A	raw float		

Table 4 – continued from previous page

Sensor/Parameter	Raw Units	Processed Units	Comments
Configuration Packet B (Source ID 0x31)			
Bin particle Volumes B	raw float		
Bin particle Densities A			
Configuration Packet C (Source ID 0x32)			
Bin particle Densities B	raw float		
Bin sample Volume Weightings A			
Configuration Packet D (Source ID 0x33)			
Bin sample Volume Weightings B	raw float		
Gain scaling Coefficient			
Sample flow Rate			
Laser DAC	raw integer		
Fan DAC			
Conversion factor			
Spare bytes			

2.2 conversion processure

2.2.1 Airsense:

• **TMP112, HTU21D, BMP180, MMA8452Q, TSYS01:** Raw outputs from the sensor boards for the sensors (TMP112, HTU21D, HIH4030, BMP180, MMA8452Q, and TSYS01) are the designated type of sensor value.

• **PR103J2:** Output of PR103J2 is an interger indicating output voltage from the sensor, which is mapped into integer values between 0 and 1023 with voltage range 0 to 3.3V. The raw integer value can be converted to resistance value through the equations below. The resistance value is needed to find corresponding temperature in a resistance-temperature look-up table (PR103J2 R-T table).

$$\text{resistance } (\Omega) = 47000 \times \left(\frac{1023}{\text{raw integer}} - 1 \right)$$

• **TSL250RD:** Output of TSL250RD in airsense board is an interger indicating output voltage from the sensor, which is mapped into integer values between 0 and 1023 with voltage range 0 to 3.3V. The raw interger value can be converted to

irradiance of visible light in micro-watt per square meter through equations below.

$$\text{irradiance } (\mu W/m^2) = \frac{\text{raw integer} \times 3.3}{1023} \times \frac{1}{0.064}$$

• **SPV1840LR5H-B:** Output value of SPV1840LR5H-B is an interger indicating amplified output voltage from the sensor, which is mapped into integer values between 0 and 1023. The raw output need to be converted to sound level in decibel (dB).

2.2.2 Lightsense

• **HMC5883L, HIH6130, and TMP421:** Raw outputs from the sensor boards for the sensors (HMC5883L, HIH6130, and TMP421) are the designated sensor value.

• **Light sensors using MCP3426 (Multiplexer) – APDS-9006-020, TSL260RD, TSL250RD, MLX75305, ML8511:** Packetized data of the ligth sensors (APDS-9006-020, TSL260RD, TSL250RD, MLX75305, and ML8511) are raw integer proportional to the output voltage from the sensor. The raw integers can be converted to irradiance through equations below.

All the sensor data coming through a common multiplexer and voltage divider, to the voltage output from the sensor is needed to calculate as shown below.

$$\text{output voltage } (V) = \text{output voltage} \times 0.0000625 \times \frac{5}{2}$$

- APDS-9006-020

  Raw output value of APDS-9006-020 is an analog voltage which is proportional to the irradiance. The output voltage can be converted irradiance in lux through the equation below.

$$\text{irradiance (lux)} = \frac{\text{output voltage}}{0.001944}$$

- TSL260RD

  Raw output value of TSL260RD is an analog voltage which is inverse proportional to the irradiance. The output voltage can be calculated though the equation below. Dark voltage is the output voltage at dark condition, and it is an unique parameter of each sensor, so that the dark voltage can be changed for individual sensor.

$$\text{irradiance } (\mu W/m^2) = \frac{\text{output voltage} - \text{dark voltage}}{0.058}$$

◦ TSL250RD

Raw output value of TSL250RD is an analog voltage which is inverse proportional to the irradiance. The output voltage can be calculated though the equation below. Dark voltage is the output voltage at dark condition, and it is an unique parameter of each sensor, so that the dark voltage can be changed for individual sensor.

$$\text{irradiance } (\mu W/m^2) = \frac{\text{output voltage} - \text{dark voltage}}{0.064}$$

◦ MLX75305

Raw output value of MLX75305 is an analog voltage which is inverse proportional to the irradiance. The output voltage can be calculated though the equation below. Dark voltage is the output voltage at dark condition, and it is an unique parameter of each sensor, so that the dark voltage can be changed for individual sensor.

$$\text{irradiance } (\mu W/m^2) = \frac{\text{output voltage} - \text{dark voltage}}{0.007}$$

◦ ML8511

Raw output value of ML8511 is an analog voltage which is proportional to the irradiance. The output voltage can be calculated though the equation below. Dark voltage, offset voltage, and UV error are unique parameters of each sensor, so that these values can be changed for individual sensor.

Dark voltage is the output voltage at dark condition, offset voltage is difference voltage between output voltage at 10 mW/cm^2 and dark voltage, and UV error is the error between real UV index and calculated UV index.

$$\text{UV index } = (\text{output voltage} - \text{dark voltage}) \times \frac{14.9916}{\text{offset voltage}} - \text{error term}$$

$$\text{error term} = \frac{14.9916}{\text{offset voltage}} - \text{UV error}$$

◦ **SPV1840LR5H-B** Raw output value of SPV1840LR5H-B is an analog voltage which is proportional to the sound level. the Raw output need to be converted to sound level in decibel (dB).

2.2.3 Chemsense

• **Chemical sensors – Total reducing gases, Nitrogen dioxide, Ozone, Hydrogen sulphide, Total oxidizing gases, Carbon monoxide, and Sulfur dioxide:** AFE ADC values need to be conversed into ppm.

• **SHT25, LPS25H:** Given values of SHT25 and LPS25H are 100ths of temperature in Celsius and 100ths of relative humidity value. If barometric pressure need to be converted in hPa, refer that hPa is 100 times of Pa.

$$\text{temperature } (^{\circ}C) = \frac{\text{output value}}{100}$$

$$\text{relative humidity } (\%RH) = \frac{\text{output value}}{100}$$

$$\text{barometric pressure } (hPa) = \frac{\text{output value}}{100}$$

• **Si1145:** Si1145 is a light sensor. Raw values coming from the sensor are three fixed hex integers, however because Chemsense board driver is not completed the values are needed to be ignored.

• **ADC Temperatures – CO ADC Temp, IAQ/IRR ADC Temp, O3/NO2 ADC Temp, SO2/H2S ADC Temp, and CO CMT Temp:** Chemsense board measures temperature of sensor ADCs. All of them give ADC temperature in 100ths of degree Celsius.

$$\text{temperature } (^{\circ}C) = \frac{\text{output value}}{100}$$

• **Accelerometer, Gyro:** Raw reading of the sensor values need to be conversed into appropreate value.

2.2.4 Alpha Sensor:

• **Histogram, Firmware, and Configuration** Raw reading of the sensor values need to be conversed into appropreate value.

3 Sensor Data

Table 5: Deta units for both raw and processed

Parameter	ID	Values	FW Output	Comments
Firmware version	0xFD	Firmware version (HW/SW)	No Units	
		Build time		
		Build git		
Airsense board				
Metsense MAC ID	0x00	MAC Address	No Unit	
TMP112	0x01	Temperature	°C	
HTU21D	0x02	Temperature	°C	
		relative humidity	%RH	
BMP180	0x04	Temperature	°C	
		Pressure	Pa	
PR103J2	0x05	Temperature	°C	
TSL250RD	0x06	Visible Light	$\mu W/m^2$	
MMA8452Q	0x07	Acceleration in X	g	
		Acceleration in Y		
		Acceleration in Z		
		Vibration		
SPV1840LR5H-B	0x08	RMS Sound Level	**N/A**	
TSYS01	0x09	Temperature	°C	
Lightsense board				
HMC5883L	0x0A	Magnetic Field in Z	G	
		Magnetic Field in Y		
		Magnetic Field in Z		
HIH6130	0x0B	Temperature	°C	
		relative humidity	%RH	
APDS-9006-020	0x0C	Ambient light intensity	Lux	
TSL260RD	0x0D	IR intensity	$\mu W/m^2$	

Continued on next page

Table 5 – *Continued from previous page*

Parameter	ID	Values	FW Output	Comments
TSL250RD	0x0E	Visible light intensity	$\mu W/m^2$	
MLX75305	0x0F	Light	$\mu W/m^2$	
ML8511	0x10	UV intensity	UV index	
TMP421	0x13	Temperature	°C	
Chemsense board				
Total reducing gases	0x15	Raw Concentration	**N/A**	
Nitrogen dioxide	0x17			
Ozone	0x18			
Hydrogen sulphide	0x19			
Total oxidizing gases	0x1A			
Carbon monoxide	0x1B			
Sulfur dioxide	0x1C			
SHT25	0x1D	Temperature	Format 2	
		relative humidity		
LPS25H	0x1E	Temperature	Format 2	
		Pressure	Format 4	
Si1145	0x1F	UV intensity	Format 1	
		Visible light intensity		
		IR intensity		
Chemsense MAC ID	0x20	MAC Address	Format 3	
CO ADC temp	0x21	ADC temperature	Format 2	
IAQ IRR ADC temp	0x22			
O3 NO2 ADC temp	0x23	ADC temperature	Format 2	
SO2 H2S ADC temp	0x24			
CO LMP temp	0x25			
Accelerometer	0x26	Acceleration in X	Format 2	
		Acceleration in Y		

Continued on next page

Table 5 – *Continued from previous page*

Parameter	ID	Values	FW Output	Comments
Accelerometer	0x26	Acceleration in X	Format 2	
		Vibration	Format 4	
Gyro	0x27	Orientation in X	Format 2	
		Orientation in Y		
		Orientation in Z		
		Orientation Index	Format 4	
Histogram	0x28	Bin count	Raw reading	
		Average Time		
		Sample flow rate		
		Temp/Pressure(alter)		
		Sampling period		
		Sum of the counts		
		PM 1		
		PM 2.5		
		PM 10		
Firmware	0x29	Firmware version		
Configuration A	0x30	Bin Boundaries		
		Bin Particle Volumes A		
Configuration B	0x31	Bin Particle Volumes B		
		Bin Particle Densities A		
Configuration C	0x32	Bin Particle Densities B		
		Bin Sample Vol Weightings A		
Configuration D	0x33	Bin Sample Vol Weightings B		
		Gain Scaling Coefficient		
		Sample Flow Rate		
Configuration D	0x33	Laser DAC and Fan DAC		
		Conversion factor		

Continued on next page

Table 5 – *Continued from previous page*

Parameter	ID	Values	FW Output	Comments
		Space Bytes		