

# tmote™ invent



## User's Manual

# moteiv

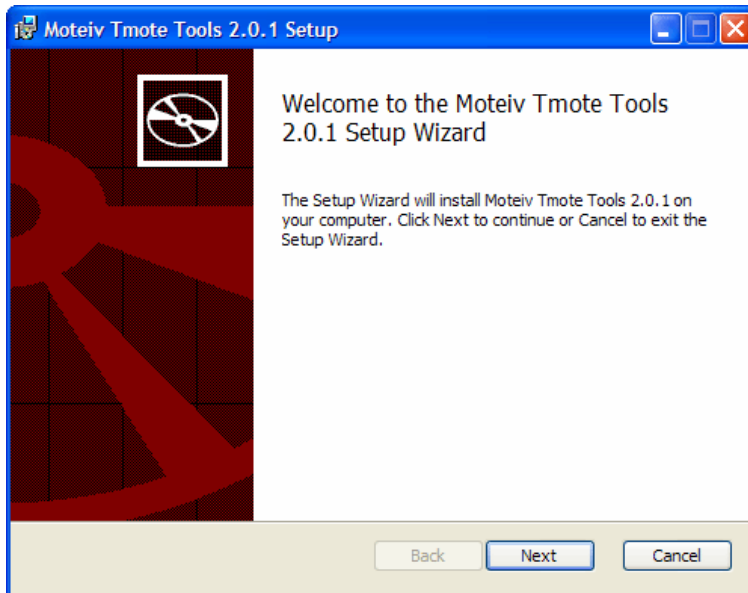
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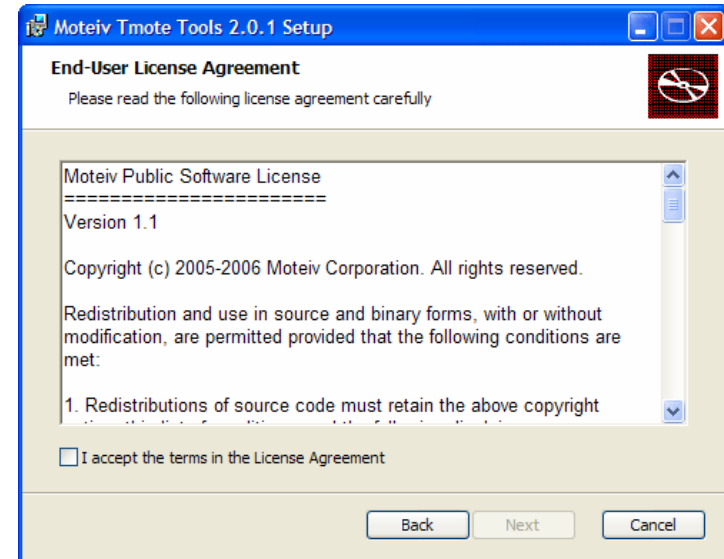
## Tmote Tools Installation

**NOTE:** If you have previously installed TinyOS or Cygwin, either from a previous Moteiv installer, from another vendor's installer, or on your own accord, we **recommend** you **remove** all previous TinyOS and Cygwin installations before proceeding. See page 20 for more information.

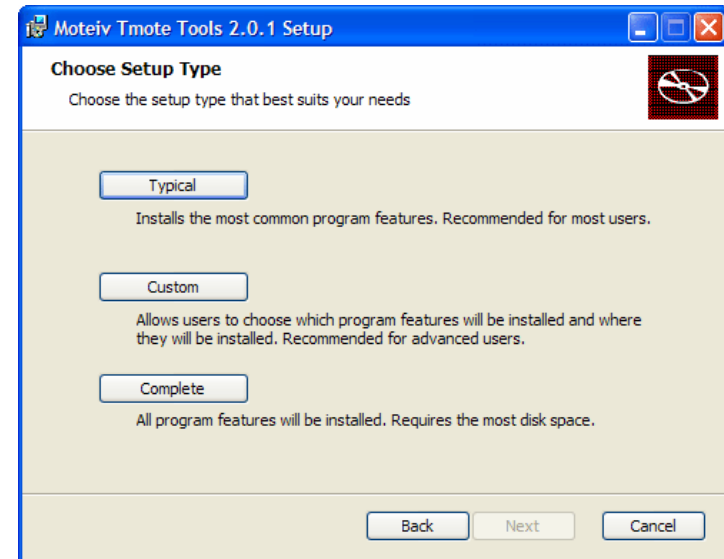
Please place the Tmote Tools CD into your computer's CD-ROM drive. After a few moments, the Moteiv Tmote Tools Setup Wizard will display:



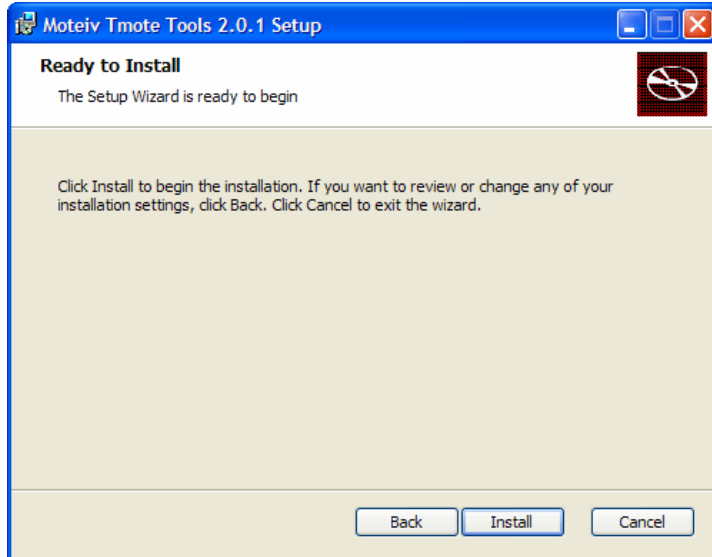
Please click "Next".



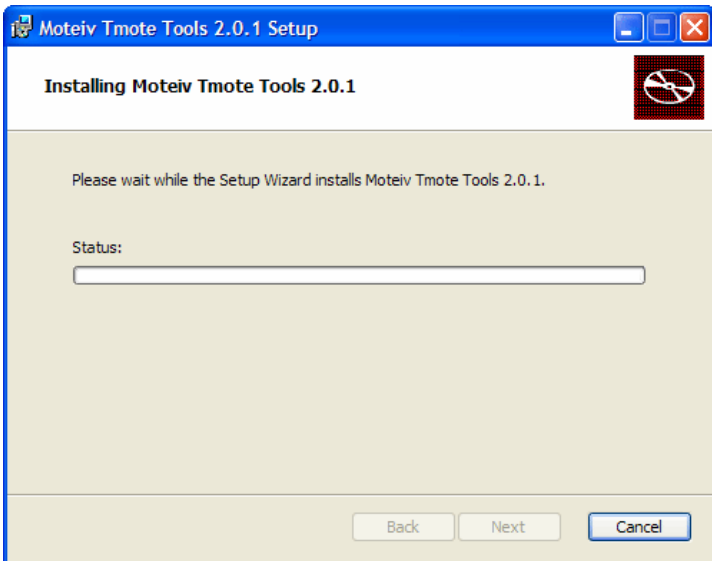
Moteiv's software is distributed under the Moteiv Public Software License. Accept the terms of the license agreement and click "Next".



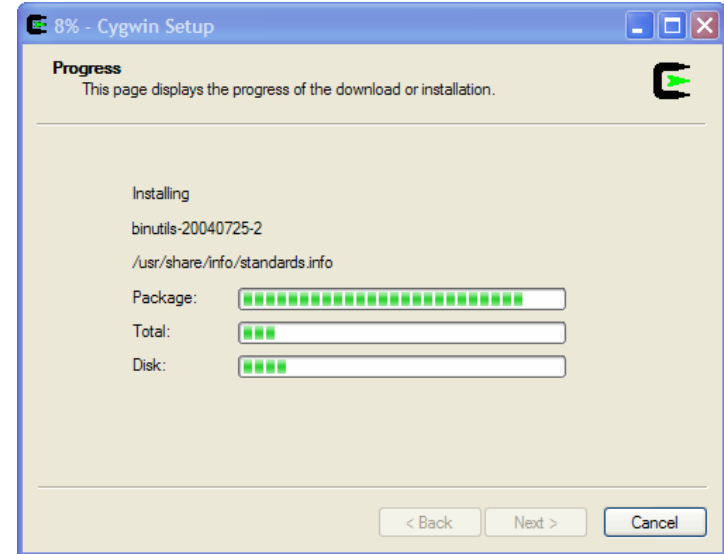
Please select the "Typical" installation option.



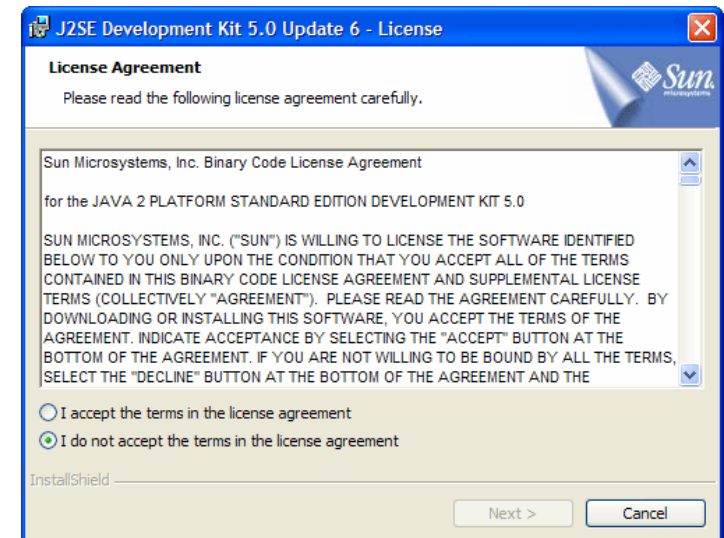
Simply click "Install".



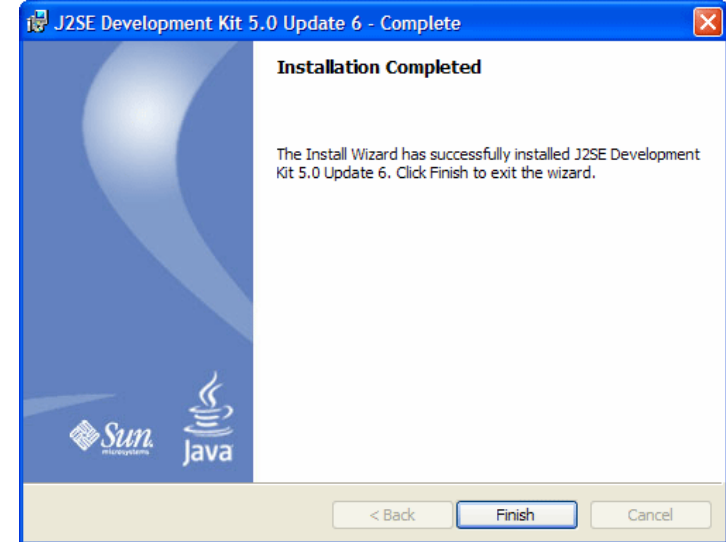
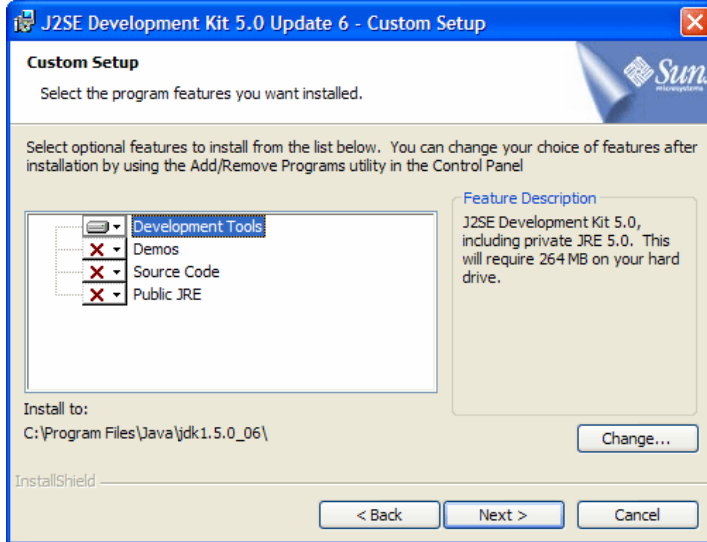
The Moteiv Tmote Tools installer will begin installation and configuration of your system.



First, the Cygwin Setup window will appear and will take a few minutes to install all of the necessary packages.

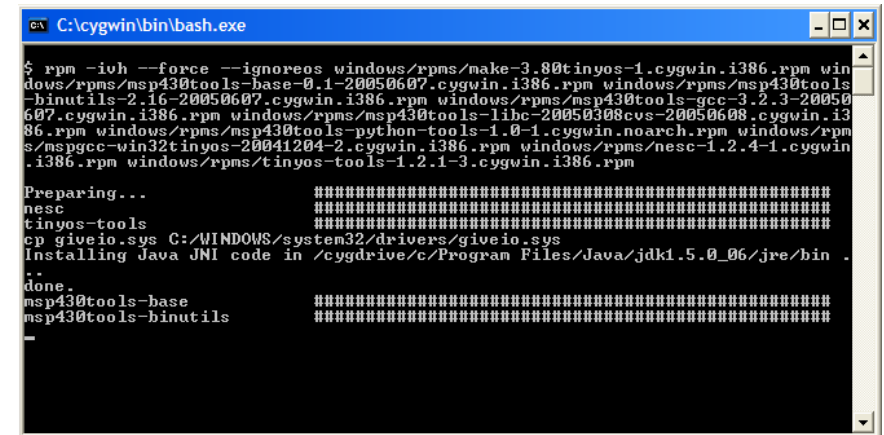
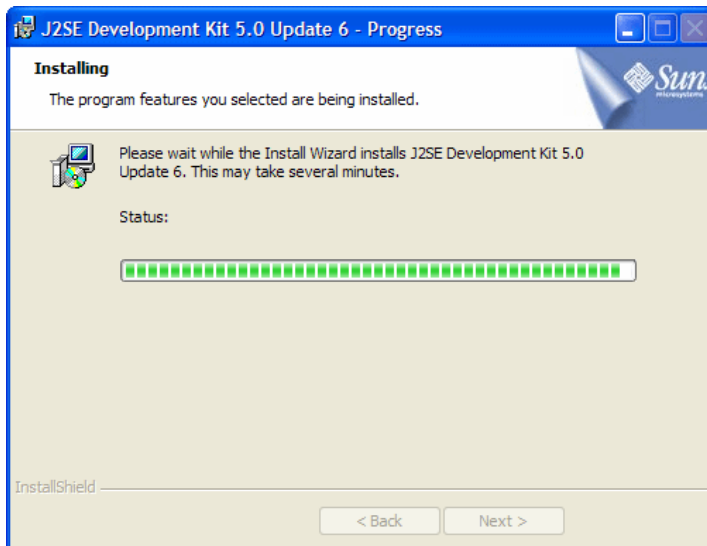


After Cygwin Setup is complete, the Java platform is installed. Accept the Sun Microsystems license agreement and click "Next".



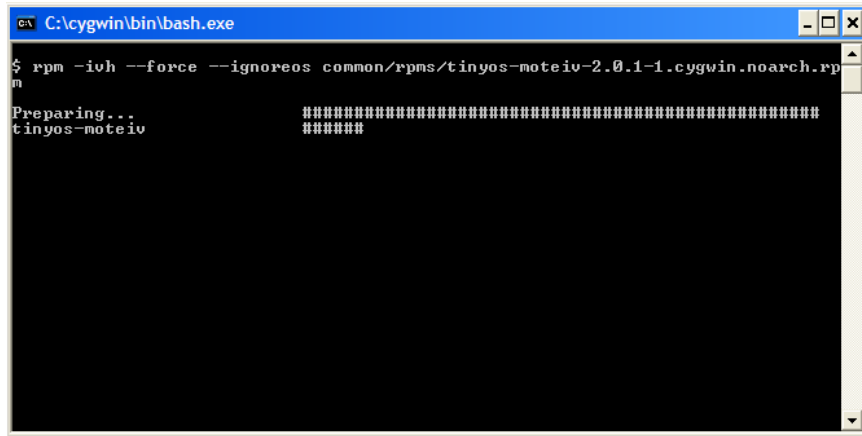
Choose additional Java installation options if desired, and then click “Next”.

Upon completion of the Java installation, click “Finish”.

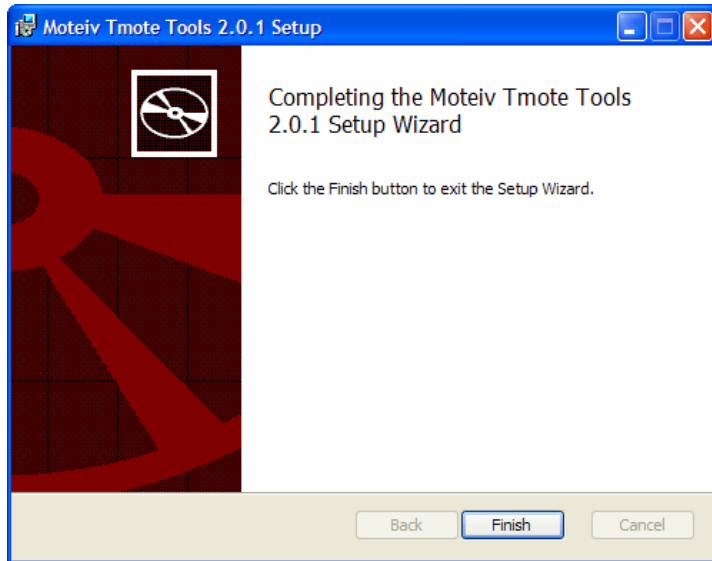


After Java is complete, the Moteiv Tmote Tools Setup Wizard will install and configure the tools required to develop and run applications using the TinyOS open source operating system. Please be patient as all of the files are installed and server tools are compiled.

The Java installer will proceed to install and configure Java.



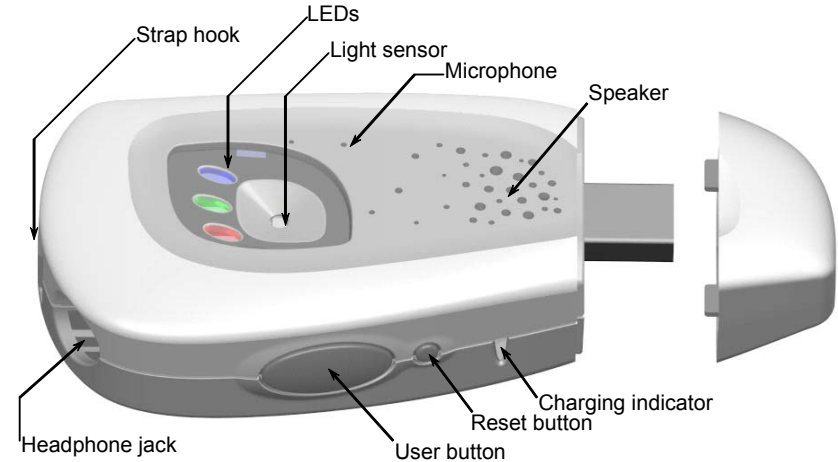
Following installation of the TinyOS tools, the Moteiv Tmote Tools Setup Wizard installs and configures Boomerang by Moteiv. This is Moteiv's distribution of the TinyOS operating system that includes extended API support, example applications, and additional development tools.



Congratulations! Installation of Moteiv's Tmote Tools is complete! Please proceed to the next section to start building applications with Moteiv's Tmote devices.

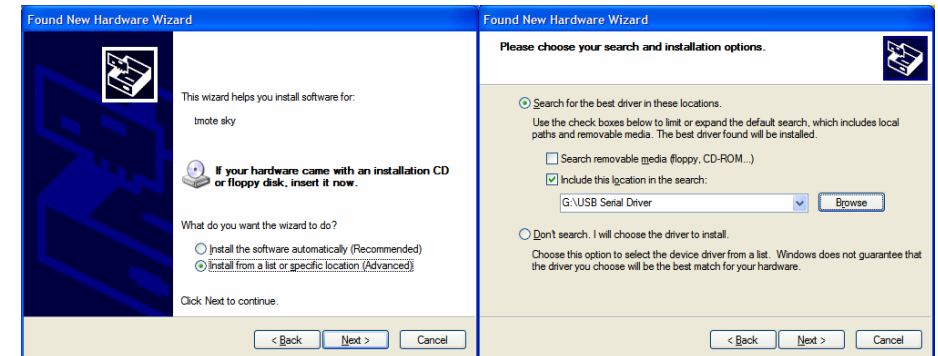
## Tmote Invent Applications

Now that Moteiv's Tmote Tools and the TinyOS development environment are installed on your system, let's explore wireless sensor networking with Tmote Invent.



Remove the Tmote Invent units from the packaging. Turn the units on by pressing the Reset button, shown in the picture above. Plug one of the units into your USB port.

If Windows displays the "Found New Hardware Wizard", select "Install from a list or specific location (Advanced)" then "Next". When prompted, select only "Include this location in the search" then click "Browse". Select the "USB Serial Driver" folder from the Tmote Tools CD, click "OK", then "Next". Windows installs the driver files, completing the installation for Tmote as a "USB Serial Port".



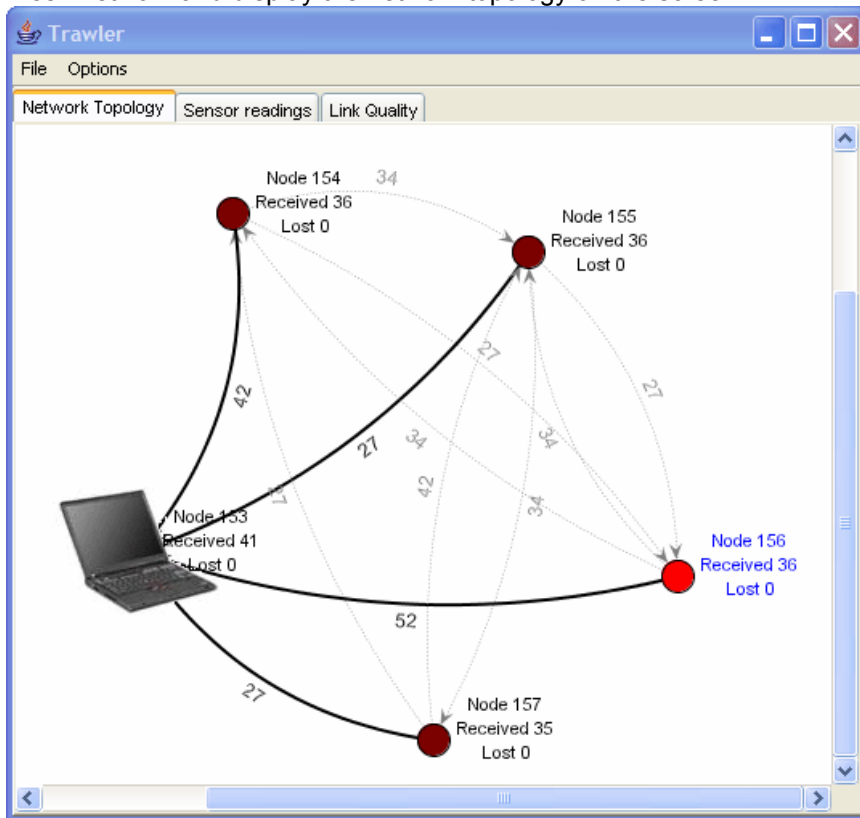


**NOTE:** To turn on Tmote Invent, press the Reset button. The LEDs will perform a 3-2-1 countdown indicating that the device is on. To turn **off** Tmote Invent, press and hold the User button. While holding the User button, press and release the Reset button. The LEDs on Tmote Invent will fade from full brightness to off, indicating the device has powered down.

Now that your Tmote Invent units are on and one is connected to the PC, run the Moteiv Trawler application. Trawler is installed on your desktop by the Moteiv Tmote Tools Setup Wizard.

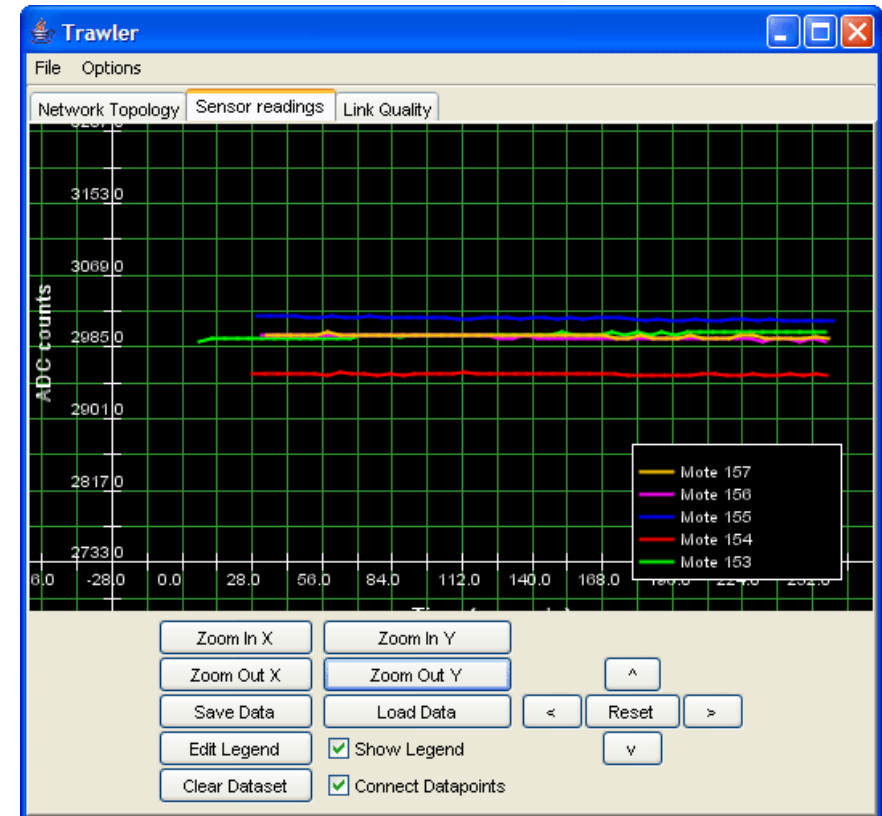


When Trawler starts, it will begin the process of establishing an ad-hoc mesh network and display the network topology on the screen.



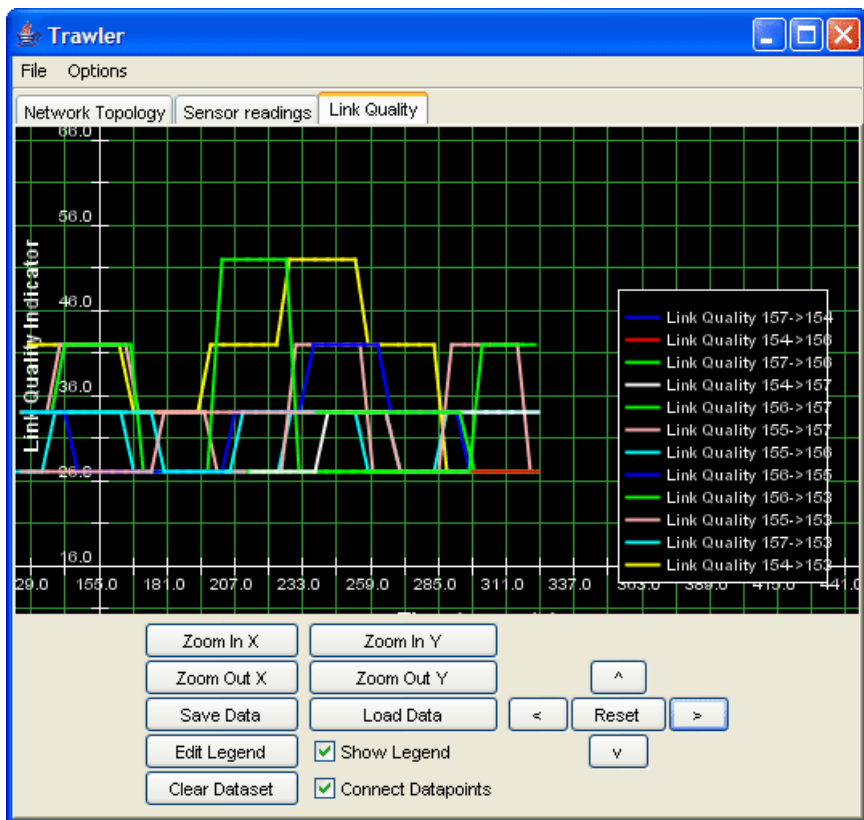
Be patient, it may take several minutes for the entire network to come online and establish stable, reliable routes to the Tmote Invent device connected to your PC.

Trawler includes a number of features to assist with standard data collection applications. By clicking on the “Sensor readings” tab, Trawler displays the temperature values coming from the nodes in the network.



Zoom in to the data by pressing the “Zoom In” and “Zoom Out” buttons. You can scroll up, down, left, and right using the arrow buttons on the bottom right of the display. You can also use your mouse to select a region on the graph—Trawler will zoom in to display the data selected.

Now, click on the “links” tab. This display assists with network commissioning—you can determine if the link quality between nodes is extremely low, you may need to move the node or add additional nodes to the network that participate in the mesh.



You can log the data readings to a file by clicking on “Log Packets” in the “Vizualization Controls” sidebar. If you cannot find the “Vizualization Controls”, minimize Trawler. Sometimes the controls are hidden by the main Trawler window.

Tmote Invent includes a few other applications, pre-installed on the Tmote Invent devices. To access these applications, first open a cygwin shell by clicking on the Cygwin icon installed on the Windows Desktop.



First, find out which port Tmote Invent is connected. Simply type `motelist` on at Cygwin command prompt.

```
$ motelist
Reference  CommPort  Description
-----
M4A663KN  COM4      tmote invent
```

In this example, Tmote Invent is connected to the PC using `COM4`, with serial number `M4A663KN`. You will need to know which communication port is assigned to your Tmote Invent unit in order to communicate with it; use the `motelist` command after connecting each Tmote Invent to identify its communications port.

To query the other applications pre-installed on Tmote Invent, run the Deluge application using the following command at the Cygwin command line:

```
MOTECOM=serial@COM4:telos java net.tinyos.tools.Deluge -p
```

Where you must replace `COM4` with the communications port returned by the `motelist` command in the step above. Deluge returns a description of the images pre-installed on Tmote Invent, as shown on the next page.

```

Pinging node ...
Connected to Deluge node.
Getting data for image [6] -----
-----
Currently Executing:
  Prog Name: Delta
  Compiled On: Mon Feb 27 16:05:46 PST 2006
  User Hash: 0xcd45b685
Stored Image 0 - (Golden Image)
  Prog Name: Delta
  Compiled On: Mon Feb 27 16:05:46 PST 2006
  Platform: tmoteinvent
  User ID: sentry
  Hostname: TestBox2
  User Hash: 0xcd45b685
  Num Pages: 33/33
Stored Image 1
  Prog Name: DeltaLowpower
  Compiled On: Mon Feb 27 16:08:00 PST 2006
  Platform: tmoteinvent
  User ID: sentry
  Hostname: TestBox2
  User Hash: 0xcd45b685
  Num Pages: 37/37
Stored Image 2
  Prog Name: Ditto
  Compiled On: Mon Feb 27 16:20:20 PST 2006
  Platform: tmoteinvent
  User ID: sentry
  Hostname: TestBox2
  User Hash: 0xcd45b685
  Num Pages: 36/36
Stored Image 3
  Prog Name: Oscilloscope
  Compiled On: Mon Feb 27 16:17:25 PST 2006
  Platform: tmoteinvent
  User ID: sentry
  Hostname: TestBox2
  User Hash: 0xcd45b685
  Num Pages: 24/24
Stored Image 4
  Prog Name: N/A
  Compiled On: N/A
  Platform: N/A
  User ID: N/A
  Hostname: N/A
  User Hash: N/A
  Num Pages: N/A
Stored Image 5
  Prog Name: N/A
  Compiled On: N/A
  Platform: N/A
  User ID: N/A
  Hostname: N/A
  User Hash: N/A
  Num Pages: N/A
-----
DONE

```

Tmote Invent is pre-installed with four applications before leaving the factory. Here is a description of each application:

| Application   | Description  |
|---------------|--|
| Delta         | Standard mesh networking application visualized using Moteiv Trawler.<br>/opt/moteiv/apps/Delta  |
| DeltaLowpower | The same as above, except that DeltaLowpower runs at a 5% duty cycle instead of 100%, significantly reducing power consumption.<br>/opt/moteiv/apps/Delta                                      |
| Ditto         | Application that records 1 second of sound from the user, disseminates it to all nodes in the network, and any Tmote Invent unit can play back the recording.<br>/opt/moteiv/apps/invent/Ditto |
| Oscilloscope  | Application that samples all of the sensors on Tmote Invent and broadcasts the readings that are displayed by a PC.<br>/opt/moteiv/apps/Oscilloscope   |

All of your nodes are currently running Delta, but with a simple command from the PC, they can switch to running Ditto. To switch your nodes from running Delta to Ditto, run the follow program (as one line of text) on the Cygwin command line:

```

MOTECOM=serial@COM4:telos
java net.tinyos.tools.Deluge -r -in=2

```

This instructs the network to reboot to image number 2.

After the nodes reboot, double click the user button on any Tmote Invent device. The mote begins a 3-2-1 countdown by flashing the red LED. When the LED turns on, Tmote Invent is recording sound using the built-in microphone. After recording, Tmote Invent disseminates the recording to all neighboring nodes. During dissemination, the blue LED flashes.

Once the blue LED stops flashing, press the user button on any Tmote Invent. The sound is played back through the Tmote Invent speaker. Repeat the process as many times as you want with any number of motes; they will continue to disseminate the recordings and play back the most recent sound sample.



After running Ditto, reboot the Tmote Invent network to the Oscilloscope application. Oscilloscope samples all of Tmote Invent's sensors and sends them over the radio for the PC to display.

To reboot to Oscilloscope, issue the following command in Cygwin:

```
MOTECOM=serial@COM4:telos
java net.tinyos.tools.Deluge -r -in=3
```

After rebooting the nodes to Oscilloscope, compile an application and install it on the mote. In Cygwin, change to the /opt/moteiv/apps/TOSBase directory. To compile an application for Tmote Invent, issue the following command:

```
make tmoteinvent
```

Upon successful compilation, your Cygwin window should display the following output, ending with:

**compiled TOSBase to build/tmoteinvent/main.exe.**

```
$ make tmoteinvent
mkdir -p build/tmoteinvent
  compiling TOSBase to a tmoteinvent binary
[verbose output omitted]
C:/cygwin/opt/moteiv/tos/lib/CC2420Radio/RadioCRCPack
et.nc:49:2: warning: #warning Using old communication
interfaces; recommend switch to SP
C:/cygwin/opt/moteiv/tos/lib/CC2420Radio/TranslateBar
eSendMsgC.nc:29:2: warning:
#warning Using old communication interfaces; recom
mend switch to SP
  compiled TOSBase to build/tmoteinvent/main.exe
      15422 bytes in ROM
      3919 bytes in RAM
msp430-objcopy --output-target=ihex
build/tmoteinvent/main.exe
build/tmoteinvent/main.ihex
  writing TOS image
```

Now install TOSBase to the node connected to the PC with the following command:

```
make tmoteinvent reinstall,1
```

where "1" is the network address assigned to the node at installation.

TOSBase is a simple base station application that forwards all messages from the radio over the USB port to the PC. This mote will be used to read the oscilloscope messages sent by other nodes.

To view the Oscilloscope readings from the other Tmote Invent units, start the Oscilloscope java application. Use motelist if necessary to determine the communications port assigned to the Tmote Invent unit running TOSBase.

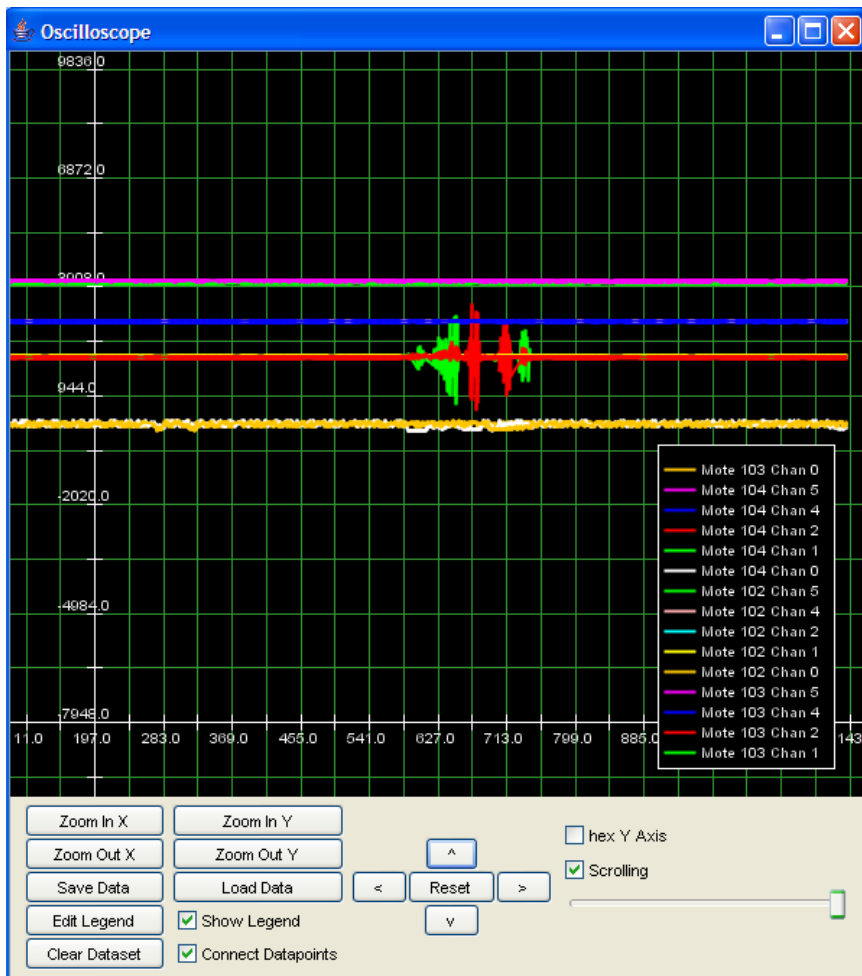
```
MOTECOM=serial@COM4:tmote
java com.moteiv.oscope.oscilloscope
```

When the Oscilloscope application executes (as shown on the next page), it displays the data readings from each of the connected motes. The data channels are assigned as follows, and all of the values displayed are raw ADC units. To convert to engineering units, see the **README.TmoteInvent** document in apps/Oscilloscope.

Channel 0: Photo  
 Channel 1: Accelerometer X-Axis  
 Channel 2: Accelerometer Y-Axis  
 Channel 4: InternalTemperature  
 Channel 5: InternalVoltage

After successfully compiling TOSBase and installing it on a node, you can reset all of your Tmote Invent devices back to their original factory image. The factory image, stored in Deluge image slot 0, can only be changed when Tmote Invent is connected directly to the PC.

To return to the factory image, press and release the reset button three times in rapid succession. The node will blink all LEDs three times to acknowledge your command, then the LEDs will flash as the factory image is reloaded into program flash. Finally, Tmote Invent will count down in the same manner as when the node is first turned on, and it will begin running the Delta application. To view readings from Delta, return to page 10 and run the Trawler application.



## Uninstalling and Upgrading

If you have previously installed TinyOS or Cygwin, either from a previous Moteiv installer, from another vendor's installer, or on your own accord, we **recommend** you **remove** all previous TinyOS and Cygwin installations before proceeding.

### Uninstalling Cygwin

Cygwin provides no method for convenient uninstall. The following steps are usually sufficient to remove Cygwin from your system:

- Close **all** Cygwin applications and services
- Delete or rename the following keys in the registry by invoking RegEdit or RegEdt32
  - HKEY\_CURRENT\_USER\Software\Cygnus Solutions
  - HKEY\_LOCAL\_MACHINE\SOFTWARE\Cygnus Solutions
- Delete or rename your Cygwin install directory, which defaults to c:\cygwin

### Uninstalling TinyOS

If you installed TinyOS with an installation utility, just run its associated uninstaller.

If not, you must manually uninstall any "tinyos", "nesc", and "msp430" RPM's. Discover which RPM's are installed by starting a Cygwin shell and running the command "`rpm -qa`". Remove packages with the command "`rpm --erase --nodeps [package1] [package2] [...]`". Here is a sample list of RPM's that may be installed, though the particular packages and versions installed on your computer may differ:

```

tinyos-tools-1.2.1-3
msp430tools-binutils-2.16-20050607
make-3.80tinyos-1
msp430tools-python-tools-1.0-1
tinyos-javacomm-1.0.0-1
tinyos-moteiv-2.0.1-1
nesc-1.2.4-1
    
```

```
msp430tools-base-0.1-20050607
msp430tools-gcc-3.2.3-20050607
msp430tools-libc-20050308cvs-20050608
mspgcc-win32tinyos-20041204-2
tinyos-1.1.15Dec2005cvs-1
```

## Upgrading Cygwin

Moteiv only supports the version of Cygwin installed by Moteiv Tmote Tools. However, any version of Cygwin installed or updated since December 2004 should be compatible, although Moteiv does not support user-installed Cygwin installations. The following Cygwin packages are installed by the Moteiv Tmote Tools CD, and are the minimum required to install TinyOS and its related tools:

```
ash autoconf autoconf-devel autoconf-stable automake auto-
make-devel automake-stable
base-files base-passwd bash binutils bison bzip2
crypt ctags cvs cygipc cygrunsrv cygutils cygwin
diffutils
editrights emacs expat
file fileutils findutils flex
gawk gcc gcc-core gcc-g++ gcc-mingw gcc-mingw-core gcc-
mingw-g++ gdb gdbm gettext gperf grep groff gzip
less libbz2_1 libcharset1 libdb4.2 libgdbm libgdbm-devel
libgdbm3 libgdbm4 libgettextpo0 libiconv libiconv2 libintl1
libintl2 libintl3 libncurses5 libncurses6 libncurses7
libncurses8 libpcre libpcre0 libpopt0 libreadline4 libread-
line5 libreadline6 login
m4 make man mingw-runtime minires mktemp more
nano ncurses
openssh openssl
patch patchutils perl perl_manpages postgresql python
rcs readline rpm rpm-build rpm-doc rxvt
sed sh-utils
tar tcltk tcsh termcap terminfo texinfo textutils time
unzip
vim
w32api wget which
zip zlib
```

## Upgrading TinyOS

Moteiv Tmote Tools installs new versions of the compilers and tools used by TinyOS. You **may** be able to directly upgrade an existing TinyOS installation using the Moteiv Tmote Tools CD, although you will be on your own if something does not work.

## Tmote Invent Hardware

Tmote Invent builds on the Tmote Sky platform by adding a number of sensors used in common applications of WSN: the device can sense light, temperature, acceleration, and sound. Tmote Invent is equipped with a full dynamic range speaker that allows for reproduction of voice-quality sounds. The device integrates a high capacity lithium ion battery that can be recharged via USB. Tmote Invent also supports a number of interactions with a user via a programmable user button and status LEDs.

### Module overview

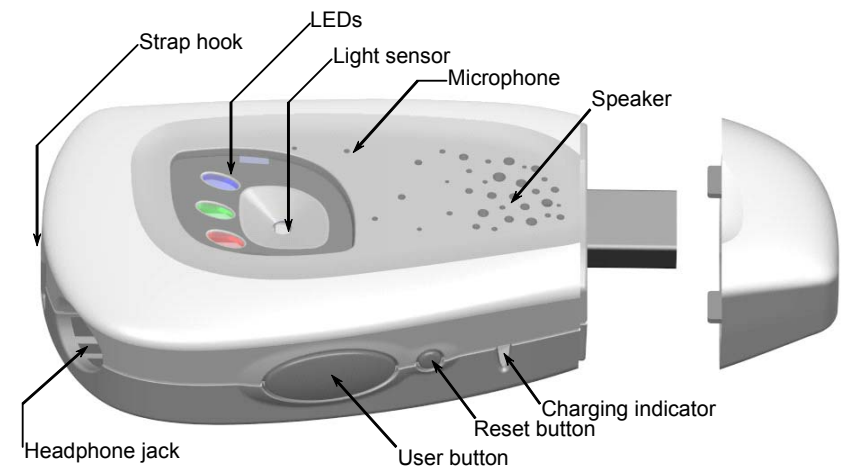
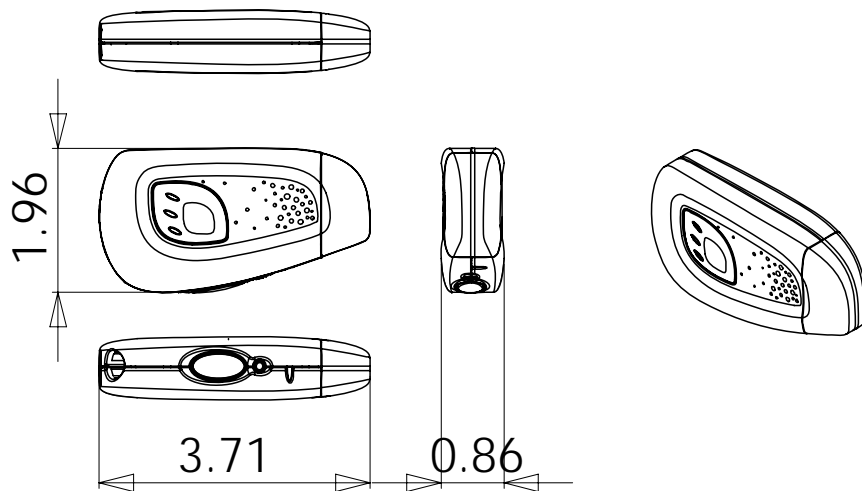


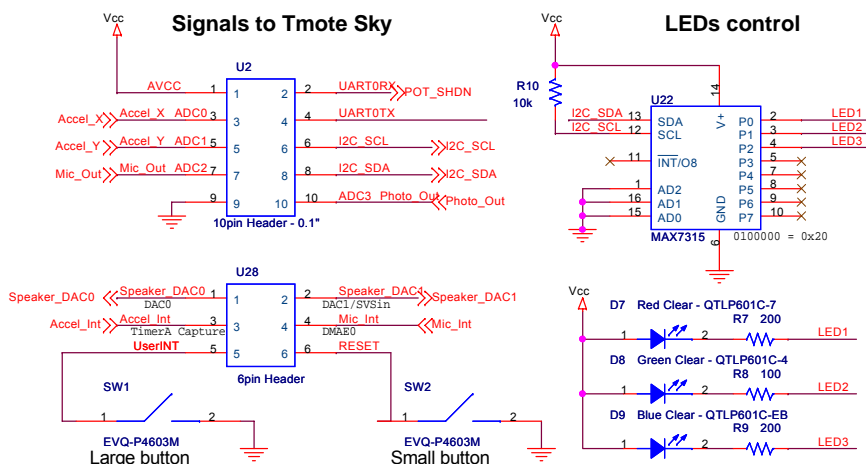
Figure 1 : Tmote Invent components

## Mechanical characteristics



All dimensions are in inches.

## Schematics



## Interface to Tmote Sky

Tmote Invent uses Moteiv's popular Tmote Sky module for communication and computation. Tmote Invent relies extensively on I2C bus for control of different sensor subcircuits. Three types of control are provided:

- I2C-activated GPIO lines – they are used throughout Tmote Invent for power and shutdown of different subcircuits
- I2C-controlled potentiometers – these are used for control of various aspects of the analog signal chain, such as adjusting amplifier characteristics and signal thresholds
- I2C LED controller is used to actuate the LEDs visible from outside the package.

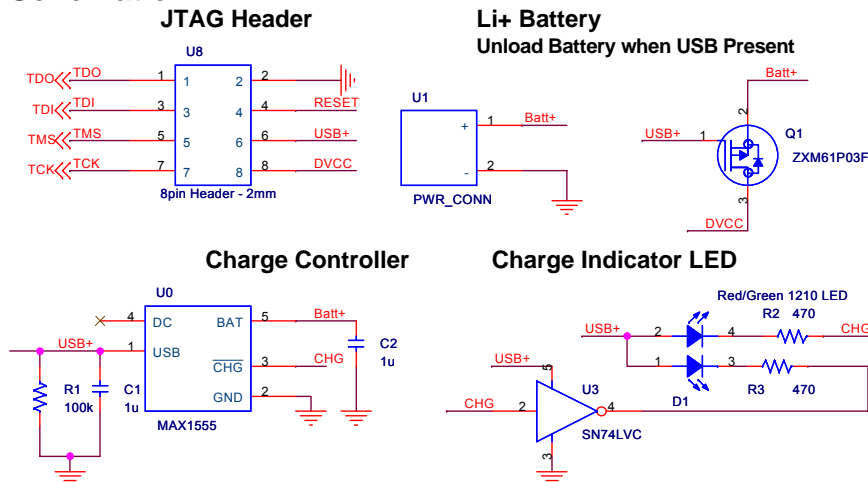
Tmote Invent uses 4 analog channels of the Tmote Sky connector for sensor data: two of these channels are dedicated to the accelerometer, one to the photo sensor, and one to the microphone. Two interrupt lines are used for analog event detection on the microphone and the accelerometer; two additional lines are used to bring the interrupts to the user accessible buttons. Finally, the speaker is driven by a single DAC signal.

For more information on Tmote Sky, please visit Moteiv's website at <http://www.moteiv.com>.

## Power Supply

Tmote invent is equipped with a lithium ion battery that is recharged when the device is plugged into a USB port. The battery provides a relatively flat discharge profile, 750 mAh capacity and 500 charge cycles. When the device is connected to a USB port, an indicator light on the left side of Tmote Invent indicates the charging status: red indicates charging, green indicates a fully charged. A full charge cycle takes about 10 hours.

## Schematic



## Battery characteristics

| Parameter             | Value     | Units   | Notes                                   |
|-----------------------|-----------|---------|---|
| Voltage range         | 3.0-4.2   | V       |   |
| Average voltage       | 3.7       | V       |   |
| Nominal capacity      | 750       | mAh     | C/5 discharge, 25 °C                    |
| Max. discharge rate   | 750       | mA      | continuous                              |
| Weight                | 16.5      | g       |   |
| Self discharge        | <10       | %/month |   |
| Operating temperature | -20 to 60 | °C      |   |
| Storage temperature   | -20 to 60 | °C      |   |
| Cycle life            | >500      |         | 150mA discharge to 80% initial capacity |

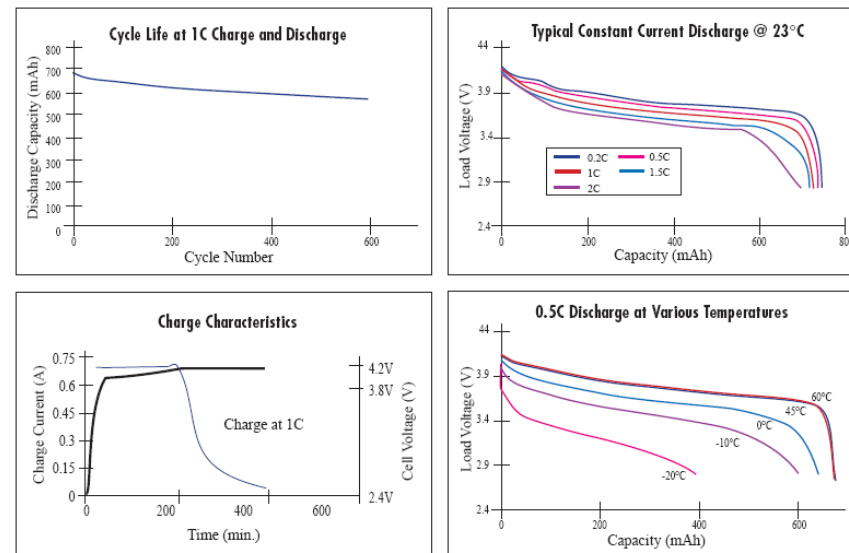


Figure 2: Rechargeable battery characteristics.

Tmote Invent is equipped with a lithium ion rechargeable battery. Figure 2 shows the various characteristics of the battery, which is rated to hold 80% of its initial capacity for over 500 cycles. The voltage ranges between 3.0 and 4.2V: the voltage region from 85% of remaining capacity to about 95% of remaining capacity is relatively flat as the voltage falls from 3.9V to 3.6V. The battery voltage may have a significant impact on the sensor performance, the user may need to consider whether the impact of this 10% variation is significant. The battery voltage will also change based on temperature, and the change is greater at small remaining capacities. When the device is plugged into the USB, the battery is charged at a rate of 80 mA; the charge conditioning is controlled via a dedicated battery charger chip, the MAX 1555. When Tmote Invent is powered via USB, the supply voltage to Tmote Invent is 3V. When the device is unplugged from the USB, occasionally the voltage transients may lead to a brown-out reset of the device.

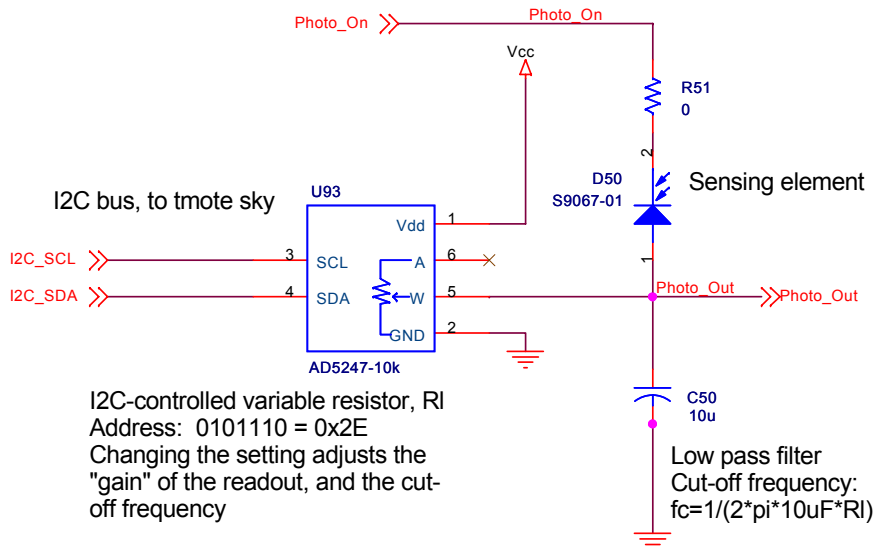
## Light sensor

Tmote Invent incorporates a high dynamic range light sensor that provides usable signal in both indoor and outdoor conditions. The spectral response is close to that of a human eye, and varies little across light sources with constant illuminance but variable color temperature. The light sensor may be used for light level measurements, lighting control, as well as for user input.

### Electrical and optical characteristics

| Parameter               | Value               | Units | Notes                      |
|-------------------------|---------------------|-------|----------------------------|
| Spectral response range | 320-820             | Nm    |                            |
| Peak sensitivity        | 560                 | Nm    |                            |
| Photocurrent            | 0.3                 | mA    | 100 lx illumination, 2856K |
| Resolution              | $8.2 \cdot 10^{-6}$ | lx    |                            |
| Power dissipation       | 75                  | mW    | Max, 5V, bright sunlight   |
| Operating temperature   | -30 to +85          | °C    |                            |
| Storage temperature     | -45 to +85          | °C    |                            |

### Schematic



### Theory of operation

The photo-sensing IC integrates two active areas on the chip. One area responds to the visible and near infrared segment of the spectrum and is used for signal detection. The second area only responds to infrared light, and is used for output signal correction. The difference between these two signals is equal to almost exactly the spectrum visible to a human eye. That difference is amplified by an internal current amplifier; the resulting signal is comparable to those from phototransistors. The output current is run through an I2C-controlled variable resistor. By changing the value of that resistor, the user can adjust the load on the circuit and adjust the voltage output that is measured by the system. The resistor has 256 equally spaced settings that take on values from 0 to 10KOhms. To obtain the photo current in mA from the ADC reading and the tap of the potentiometer, the following formula should be used:

$$I_l = ADC \cdot \frac{1.5}{160 \cdot P_{tap}}$$

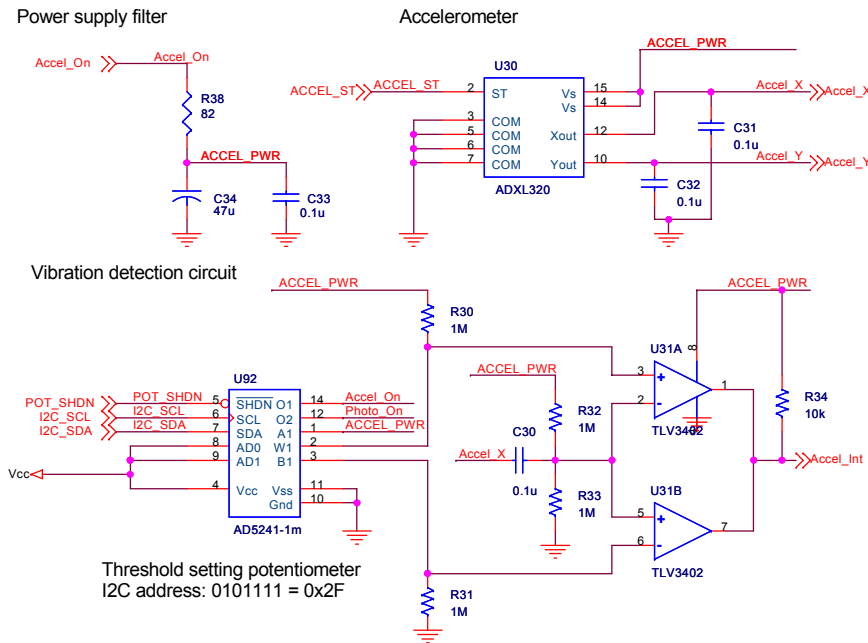
where the ADC is the number obtained from the onboard analog to digital converter (a number between 0 and 4095), and  $P_{tap}$  is the tap setting of the variable resistor (a number between 0 and 255). When the ADC count is low, user software should increase the tap of the variable resistor, thereby increasing the gain on the output.



## Accelerometer

Tmote Invent's accelerometer senses 2-axis acceleration in the plane of the device. The accelerometer provides measurements in the range of  $\pm 5g$  with a bandwidth of 50Hz. In addition to the simple sampling with an analog-to-digital converter, the circuit provides an adjustable threshold detector on the X-axis, which allows the mote to detect vibration events with the microcontroller running in low power mode. The accelerometer is suitable for vibration measurements, orientation detection, gesture recognition and a variety of other motion- and tilt-detection systems.

## Schematic



## Electrical and mechanical characteristics

| Parameter             | Value     | Units             | Notes                      |
|-----------------------|-----------|-------------------|----------------------------|
| Range                 | $\pm 5$   | g                 |                            |
| Sensitivity           | 156-192   | mV/g              | $V_{cc}=3V$                |
| Sensitivity change    | 0.01      | $\%/^{\circ}C$    | with temperature           |
| Resolution            | 3.91      | mg                | $V_{cc}=3V, V_{ref}=2.5V$  |
| 0g voltage bias       | $\pm 0.2$ | V                 | From $V_{cc}/2, V_{cc}=3V$ |
| 0g voltage change     | $\pm 0.6$ | $mg/^{\circ}C$    | with temperature           |
| Noise density         | 250       | $\mu g/\sqrt{Hz}$ | RMS, @25 $^{\circ}C$       |
| Frequency response    | 0-50      | Hz                | -3dB cutoff                |
| Turn-on time          | 20        | ms                |                            |
| Power dissipation     | 490       | $\mu A$           |                            |
| Operating temperature | -20-70    | $^{\circ}C$       |                            |
| Storage temperature   | -65-150   | $^{\circ}C$       |                            |

## Theory of operation

The accelerometer subcircuit is built around ADXL 320 from Analog Devices. The accelerometer has a measurement range of  $\pm 5g$  and it has been configured to sense acceleration frequencies from 0 to 50 Hz. The output signals are analog voltages proportional to the acceleration. The system measures static acceleration forces, which allows it to be used as a tilt sensor. In addition to the typical sampling, the circuit may be software-programmed to provide a wakeup interrupt to the microcontroller whenever the acceleration exceeds a programmed level.

The accelerometer part contains a polysilicon surface micromachined sensor and signal conditioning circuitry. Polysilicon springs suspend the sensing structure over the surface of the wafer and provide the resistance against the acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and plates attached to the moving mass. The fixed plates are driven by 180° out-of-phase square waves. Acceleration deflects the beam and unbalances the differential capacitor, resulting in an output square wave whose amplitude is proportional to acceleration. Phase-sensitive demodulation techniques are then used to rectify the signal and determine the direction of the acceleration.

In Tmote Invent, the accelerometer has been configured for a nominal bandwidth of 50Hz. Because of process variations of an internal resistor, the actual bandwidth may vary by  $\pm 15\%$ . In order to avoid aliasing, it is recommended that the accelerometer be sampled at a rate of at least 115 Hz. The ADXL320 noise has the characteristics of white Gaussian

noise, which contributes equally at all frequencies and is described in terms of  $\mu\text{g}/\sqrt{\text{Hz}}$ . At the configured bandwidth, the RMS noise is 2.25 mg. Peak-to-peak noise can only be estimated by statistical methods, the table below shows the estimates for the probabilities of a peak-to-peak noise given the RMS values. For a single measurement, the peak-to-peak noise estimate is 13.5 mg.

| Peak-to-peak value | % time that noise exceeds that value |
|--------------------|--------------------------------------|
| 2x RMS             | 32                                   |
| 4x RMS             | 4.6                                  |
| 6x RMS             | 0.27                                 |
| 8x RMS             | 0.006                                |

The accelerometer performance varies little with temperature. Across -20 —70 °C the sensor shows less than 1% change in sensitivity. The temperature change of the 0g offset is linear, and with two-point calibration, can be compensated to within 3mg.

The accelerometer has a built-in self test feature. When the ACCEL\_ST signal is set to Vcc, an electrostatic force is exerted on the beam. The resulting movement of the beam allows the user to assert whether the accelerometer is functional. The typical change in the output signal is 315 mg or 0.55 V. In common usage this signal should be set to 0V (default).

The vibration detection circuit allows the user to generate an interrupt whenever the acceleration exceeds the programmed levels. The X-axis of accelerometer is AC-coupled into a pair of comparators: one comparator detects the swings into the upper acceleration bound; the other detects the swings into the lower acceleration bound. The spacing of the lower and upper bands is set via an I2C-controlled potentiometer with 256 taps. The acceleration bounds  $v_{thresh}$ (in V) and  $a_{thresh}$  are related to the potentiometer *tap* setting via:

$$v_{thresh} = \pm \frac{V_{cc}}{2} \cdot \left( 1 - \frac{512}{(tap + 512)} \right)$$

$$a_{thresh} = \pm \frac{V_{cc}}{2 \cdot a_{sensitivity}} \cdot \left( 1 - \frac{512}{(tap + 512)} \right)$$

Assuming the nominal sensitivity of 174mV/g and voltage supply at 3V, the acceleration thresholds  $a_{thresh}$  in g can be obtained via the following formula:

$$a_{thresh} = \pm 8.6 \cdot \left( 1 - \frac{512}{(tap + 512)} \right)$$

The accelerometer characteristics depend on supply voltage. The lithium ion battery of Tmote Invent provides a voltage between 3 and 4.2V; when the unit is connected to a USB port, it is powered with a 3V supply. The individual characteristics are affected as follows:

- Output is ratiometric, so output sensitivity varies proportionally to supply voltage. At the typical battery voltage of 3.6V the typical sensitivity is 209 mV/g
- Moteiv recommends reading the accelerometer readings using the supply voltage (Vcc) as the reference voltage for the analog-to-digital converter. When Vcc is used as the reference, 0g is centered around 2048 ADC units, and 1g of acceleration is equal to 245 ADC units regardless of supply voltage.
- 0g bias is ratiometric, nominally  $V_{cc}/2$ .
- The output noise is absolute in V; as the supply voltage and sensitivity increase, the noise density decrease.
- Self-test response in mg is proportional to the square of the supply voltage. When the resulting increase in sensitivity is factored in with supply voltage, the self-test response in volts is proportional to the cube of the supply voltage.
- Supply current increases roughly linearly with the supply voltage.

## Microphone

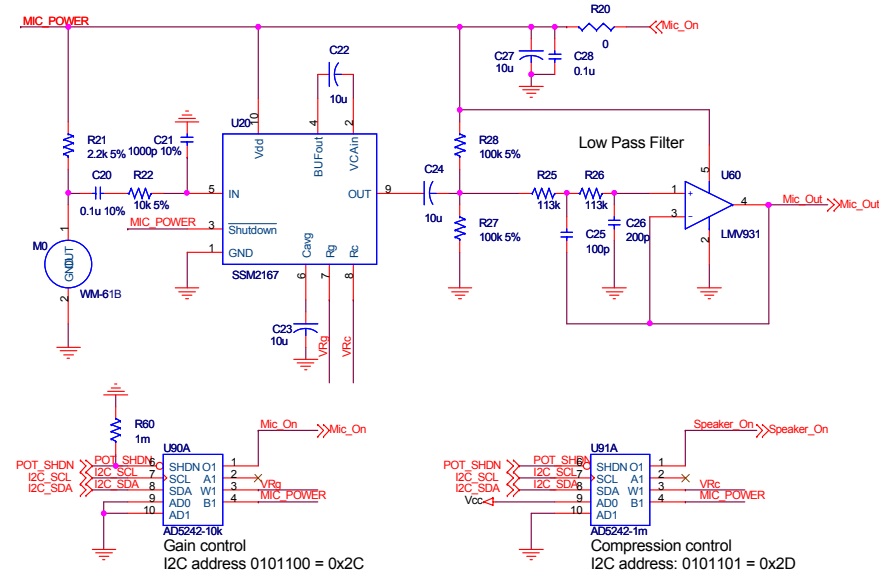
Tmote Invent microphone circuit allows for omnidirectional acquisition of sounds in the range of 20-10000Hz. The amplification circuit of the microphone provides variable compression ratio that allows for large-scale amplification of low-volume signals while preventing clipping of the high volume inputs. Variable noise gating prevents the amplification of background noise. Taken together, these characteristics provide powerful processing of voice-band signals. The circuit also features a programmable wakeup that can be set to provide a system interrupt when input signals exceed desired volume. The microphone may be used for voice and sound input, as well as noise detection. Taken together with Tmote Invent's speaker system, it forms a basis for two-way voice communication, environmental characterization, and acoustic ranging.

### Electrical and acoustic characteristics

| Parameter                               | Value      | Units  | Notes  |
|---|------------|--------|--|
| <b>Microphone</b>                       |            |        |  |
| Sensitivity                             | -35±4      | dB     | 0dB=1V/pa, 1kHz  |
| Frequency response                      | 20-20000   | Hz     | Final step in the signal chain is 10kHz 2 <sup>nd</sup> order LPF. |
| <b>Audio path</b>                       |            |        |  |
| Voltage noise density                   | 20         | nV/√Hz | 10:1 compression   |
| Noise                                   | -70        | dBV    | 20kHz BW, Vin=GND  |
| THD+noise                               | 0.2        | %      | Vin=100mV RMS  |
| <b>Control section</b>                  |            |        |  |
| VCA dynamic gain                        | 40         | dB     |  |
| VCA fixed gain                          | 18         | dB     |  |
| Compression ratio, min                  | 1 : 1      |        |  |
| Compression ratio, max                  | 10 : 1     |        |  |
| Rotation point                          | 63         | mV     | RMS  |
| Noise gate range                        | -40 to -55 | dBV    |  |
| <b>Power, timing, temperature range</b> |            |        |  |
| Turn-on time                            | 200        | ms     |  |
| Shutdown time                           | 1          | ms     | Shutdown via power-down; shutdown via signal takes 1s              |
| Power consumption                       | 2.3        | mA     |  |
| Operating temperature                   | -40-85     | °C     |  |
| Storage temperature                     |            |        |  |

### Schematic

#### Microphone Analog Signal Conditioning



#### Microphone Acoustic Wakeup

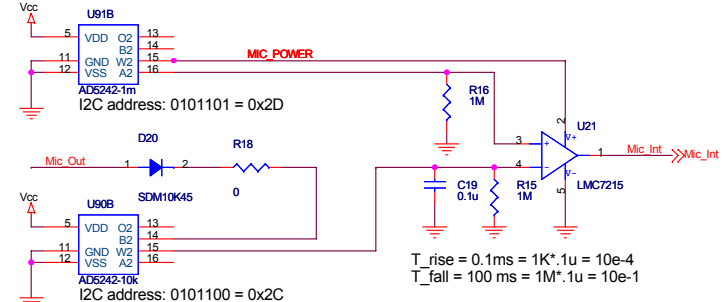
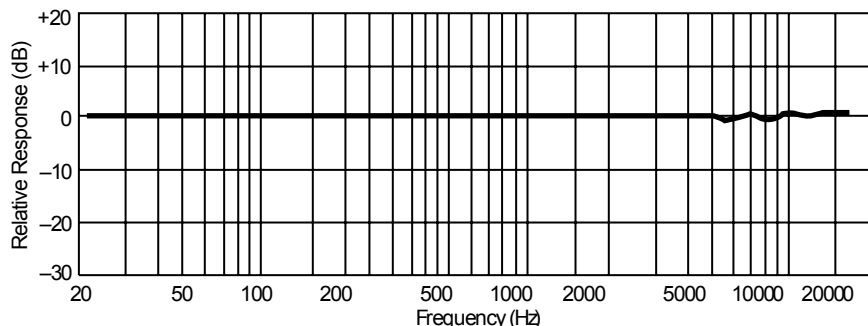


Figure 3: Microphone subcircuit schematic

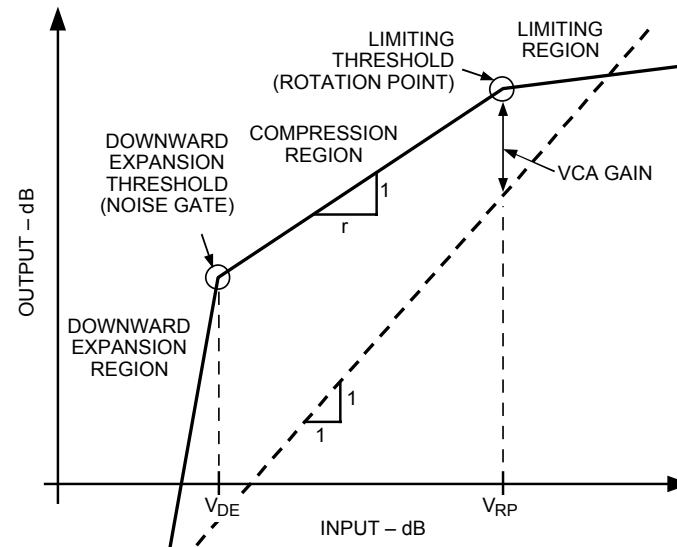
### Theory of operation

The circuit is built around an omnidirectional electret microphone WM-61B made by Panasonic. The output signal from the microphone is processed by an Analog Devices SSM2167 preamplifier with variable compression ratio and noise gating. The amplified signal is filtered through a 2<sup>nd</sup> order Butterworth low pass filter with a cutoff frequency of 10 kHz, and passed to both an analog-to-digital converter and to the acoustic wakeup circuit. The acoustic wakeup circuit features a programmable envelope detector and a settable threshold.



**Figure 4: Spectral response of the microphone**

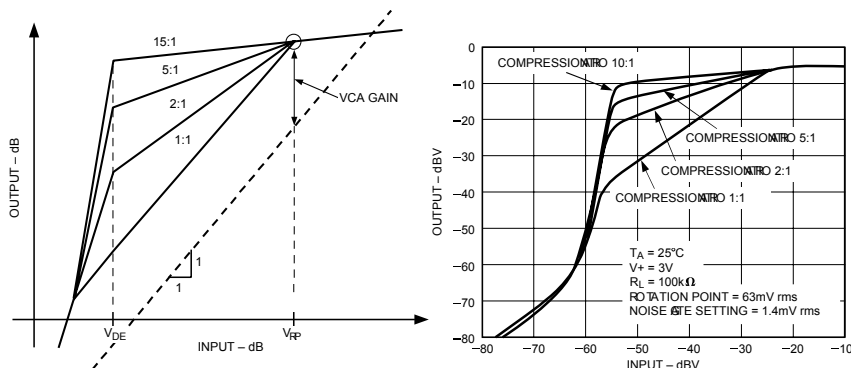
The conditioning of the microphone signal is done by the Analog Devices SSM2167 chip. At the core of the IC is a voltage-controlled amplifier that provides a gain that is dynamically adjusted by a control loop to maintain a set compression characteristic. The compression ratio is set by a single resistor and can be varied from 1:1 to over 10:1 relative to the fixed rotation point. Signals above the rotation point are limited to prevent overload and to eliminate popping. A downward expander (noise gate) prevents amplification of background noise or hum. The typical transfer characteristics for the SSM2167 are shown in Figure 5.



**Figure 5: Transfer characteristics for SSM2167.**

In Figure 5, the output level in dB is plotted against the input level in dB. The dashed line denotes the transfer characteristics of a unity gain amplifier. For input signals at  $V_{RP}$ , the circuit provides a fixed gain of 18 dB. For input signals in the range between  $V_{RP}$  and  $V_{DE}$ , an  $r$  dB decrease in the input signal will produce a 1 dB decrease in output. This region is defined as “compression region” and compression ratio of  $r:1$ . The compression ratio may be varied via a potentiometer setting between 1:1 (no compression, fixed 18 dB gain) and 10:1. Input signals above  $V_{RP}$  are compressed with a fixed compression ratio of about 10:1 and this region is called the limiting region. Note that  $V_{RP}$  is fixed at -24dB and varying the compression ratio has no effect on the compression in the limiting region. Input signals at levels lower than  $V_{DE}$  are downward expanded: a 1 dB decrease in the input signal will produce a 3 dB decrease in the output. As a result, the system gain is small at low input levels even though it may be quite large in the range just above  $V_{DE}$ .  $V_{DE}$  may be set in the range of -40 -- -55 dBV via setting of a potentiometer. When  $V_{DE}$  is set to -55 dBV, the maximum gain at  $V_{DE}$  is 46 dB and is obtained at 10:1 compression ratio.

In Tmote Invent the compression ratio is controlled via an I2C-controlled potentiometer. The compression will not affect the gain at the VRP, but will have a great effect on amplification of low signals. Figure 6 shows the effects of different compression ratios on the amplification.

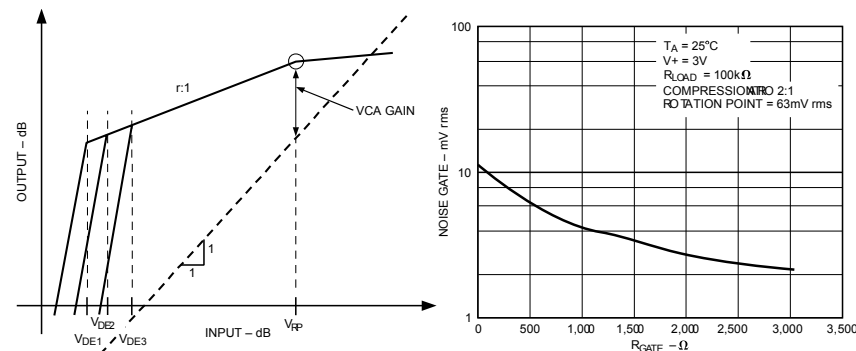


**Figure 6: Effects of varying the compression ratio (schematic view and measurement).**

For ratios above 1.2:1, the compression ratio  $r:1$  is related to the potentiometer tap setting  $P_{tap}$  via:

$$r = \frac{P_{tap} \cdot 50}{256} + 1.2$$

The noise gate threshold  $V_{DE}$  is set via an I2C controlled potentiometer. The threshold may be set between -40 and -55 dBV. Figure 7 illustrates the effect of different settings of noise gate threshold. The threshold setting is inversely proportional to the resistance  $R_{WB}$  of the I2C-controlled potentiometer: at a tap setting of 0 the threshold is set to approximately 10 mV RMS, and at tap setting of 128 (5 kΩ) the threshold is set at approximately 1mV. It is not recommended to use potentiometer settings above 128; at those settings the noise floor is over-amplified beyond the device's limits causing problems. Table 2 summarizes the most commonly used settings.



**Figure 7: Effects of varying the noise gate (downward expansion) threshold (left). The relationship between  $R_{GATE}$  and the noise gate setting (right).**

| Compression ratio | Value of $R_{WB}$ | Pot setting | Max. gain |
|-------------------|-------------------|-------------|-----------|
| 1:1               | <5                | 0           | 18        |
| 2:1               | 15                | 4           | 33.5      |
| 3:1               | 35                | 9           | 38.5      |
| 5:1               | 75                | 19          | 40        |
| 10:0              | 175               | 45          | 46        |

**Table 1: Commonly used compression ratio settings and corresponding potentiometer settings, maximum gain is attained at the lowest  $V_{DE}$  setting of -55 dBV.**

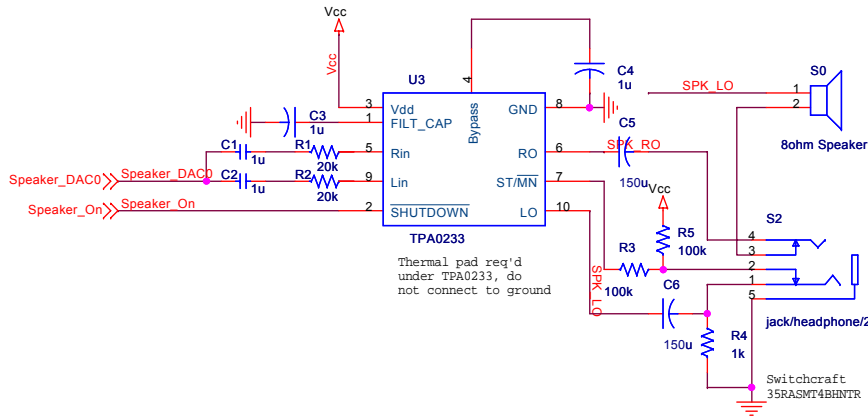
| Noise gate | Value of $R_{GATE}$ | Pot setting |
|------------|---------------------|-------------|
| -40        | 0                   | 0           |
| -48        | 1                   | 26          |
| -54        | 2                   | 51          |
| -55        | 5                   | 128         |

**Table 2: Common settings of noise gate threshold**

## Speaker

Tmote Invent is equipped with a full dynamic range speaker, providing on demand sound output. The sound may either be output to a speaker or to user-supplied headphones. The speaker provides nearly 1W output at a wide frequency response. It can be used to produce voice output and a wide variety of frequency tones. The speaker, with user software, may be used in acoustic ranging applications.

## Schematic



## Electrical and acoustic characteristics

| Parameter              | Value         | Units    | Notes                  |
|------------------------|---------------|----------|------------------------|
| <b>Speaker</b>         |               |          |                        |
| Impedance              | 8             | $\Omega$ |                        |
| Frequency range        | 400 to 20,000 | Hz       |                        |
| Resonant frequency     | 620           | Hz       |                        |
| Sensitivity            | 80            | dB       | +/-3dB                 |
| Nominal power output   | .75           |          |                        |
| Maximal power output   | 1.1           |          |                        |
| <b>Power Amplifier</b> |               |          |                        |
| Current consumption    | 3.3           | mA       | Max 5mA                |
| Shutdown current       | 1             | $\mu$ A  |                        |
| Output power at 3.6V   | 650           | mW       | 8 $\Omega$ speaker     |
| Output power at 3.6V   | 40            | mW       | 32 $\Omega$ headphones |
| Maximum bandwidth      | 20            | kHz      |                        |
| Total distortion       | 0.3%          | THD+N    | 200Hz to 20kHz         |
| Lowest frequency       | 133           | Hz       | 8 W speaker            |
| Lowest frequency       | 33            | Hz       | 32 W headphones        |

## Theory of operation

The speaker subsystem on Tmote Invent is designed to output sound, either to an integrated 1W speaker or to a standard 1/8" headphone jack. Tmote Invent's speaker can be driven at levels of 650 mW across a broad frequency range. User-supplied headphones may be used to reproduce an even broader spectrum of sound. Tmote Invent uses a single DAC channel to drive both channels of the audio power amplifier. The configuration is optimized for minimal resource usage when driving the speaker. When operating with headphones, identical sound output will be heard in left and right channels. The amplifier exhibits very low distortion, both across power output levels and across frequency, as shown in Figure 9.

The input stage of the power amplifier is decoupled from the DAC channel by a high pass filter with a corner frequency of 8Hz. For outputs with impedances of over 64 $\Omega$  that filter becomes the limiting stage in the frequency response. The input signal is then amplified by a factor of 3.125 when the output is directed to the headphones and by a factor of 6.25 when the output is directed to the speaker. In order to avoid clipping and allow a bit of headroom, the input signal needs to be 1/6 of the full scale when driving the speaker and 1/3 of the full scale when driving the headphones. The table below shows the mean of the signal and the maximum amplitude that can be reproduced without clipping.

|           | Signal characteristics<br>8 bit DAC | Signal characteristics<br>12 bit DAC |
|-----------|-------------------------------------|--------------------------------------|
| Speaker   | 128 $\pm$ 20                        | 2048 $\pm$ 328                       |
| Headphone | 128 $\pm$ 41                        | 2048 $\pm$ 655                       |

The power stage consists of two Class-AB audio power amplifiers. In headphone mode, each amplifier drives a separate audio channel. When driving the speaker, the two amplifiers operate in a bridge-tied load (BTL) configuration: one power amplifier is directly connected to the load; the output of the other power amplifier is inverted and used to drive the other end of the load. As a result, the system is capable of delivering output levels that are 6 dB louder than those produced by a single ended configuration.

The amplifier may be put into a shutdown mode by setting the **SPEAKER\_ON** signal to low. In shutdown mode, the power amplifier typically draws less than 1  $\mu$ A. When turned on, and driven with no signal,



the power amplifier draws about 3.3 mA. Both the maximum power output and the current drawn by the amplifier depend on battery voltage, Figure 8 details that dependency. When actively amplifying the signal, the system shares the inefficiencies of all Class-AB amplifiers. The amplifier efficiency  $\eta$  is related to the power delivered to the speaker  $P_L$  by the formula

$$\eta = \frac{\pi \sqrt{2P_L R_L}}{4V_{CC}}$$

Tmote Invent's speaker presents a load  $R_L$  of  $8\Omega$ . The power is related to the peak voltage by

$$P_L = \frac{V_{Peak}^2}{2R_L}$$

The amplifier efficiency is proportional to the peak voltage. The energy not converted to sound is dissipated as heat. At its peak, with the peak voltage of 2.3V, the power amplifier dissipates 0.33W as heat; temperature sensitive applications may need to account for the resulting changes.

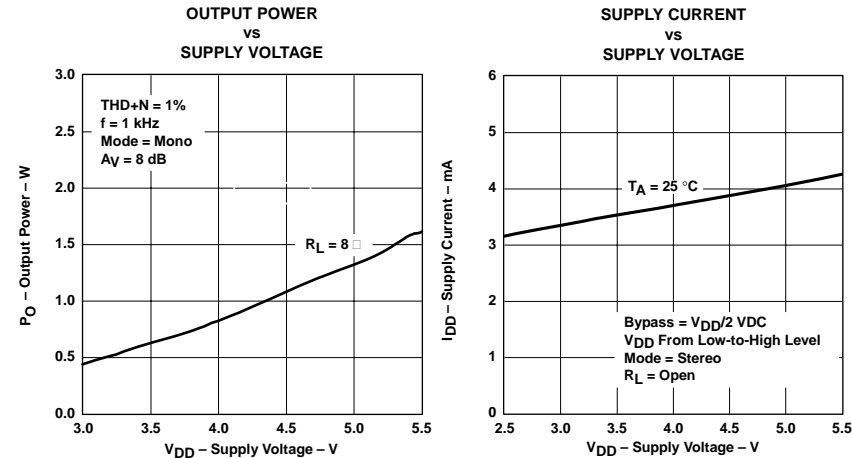


Figure 8 : Output Power and Supply Current as a function of Supply Voltage

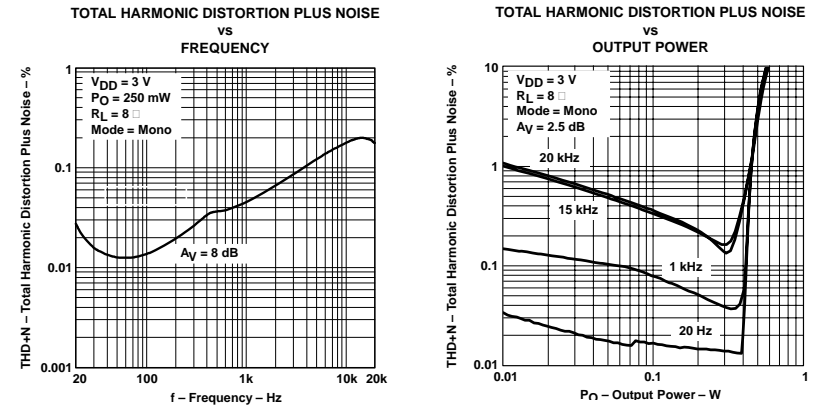


Figure 9 : Total Harmonic Distortion plus Noise as affected by frequency and output power

## Tmote Invent Software

Tmote Invent includes Moteiv's TinyOS software providing a complete system for building wireless sensing applications. TinyOS consists of drivers (called "components") that provide useful interfaces for accessing the functionality of Tmote Invent. Below, the components and corresponding interfaces for sensing and communication are shown; for more in-depth descriptions of these components and interfaces, please view Moteiv's API documentation by opening [index.html](#) document inside of `/opt/moteiv/docs/nosdoc`

### Sensor Drivers

The sensors on Tmote Invent each include a corresponding TinyOS driver. Please refer back to each sensor's theory of operation for documentation that describes how to interpret values from the sensors, set potentiometer values, and enable interrupts.

#### Accelerometer

TinyOS Driver: `AccelDriverC`

Location: `/opt/moteiv/tos/sensorboards/invent/`

| Interface  | Function                       |
|--|--------------------------------|
| SplitControl   | Turn on/off sensor             |
| ADC as <b>AccelX</b>                                 | Read X-axis value              |
| ADC as <b>AccelY</b>                                 | Read Y-axis value              |
| Potentiometer as <code>AccelInterruptSettings</code> | Set Interrupt Threshold        |
| SensorInterrupt as <b>AccelInterrupt</b>             | Handle Accelerometer Interrupt |

#### Light Sensor

TinyOS Driver: `PhotoDriverC`

Location: `/opt/moteiv/tos/sensorboards/invent`

| Interface           | Function              |
|---------------------|-----------------------|
| SplitControl        | Turn on/off sensor    |
| ADC as <b>Photo</b> | Read Photo value      |
| Potentiometer       | Set Photo sensor gain |

#### Microphone Sensor

TinyOS Driver: `MicDriverC`

Location: `/opt/moteiv/tos/sensorboards/invent`

| Interface   | Function                        |
|---|---------------------------------|
| SplitControl  | Turn on/off sensor              |
| ADC as <b>Mic</b>                                   | Read single Microphone value    |
| Microphone  | Read large Microphone buffers   |
| Potentiometer as <b>Vrc</b>                         | Set preamp compression ratio    |
| Potentiometer as <b>Vrg</b>                         | Set preamp noise gate threshold |
| Potentiometer as <b>MicInterruptDrain</b>           | Set RC drain time on interrupt  |
| Potentiometer as <code>MicInterruptThreshold</code> | Set amplitude for interrupt     |
| SensorInterrupt as <b>MicInterrupt</b>              | Handle Microphone Interrupt     |

#### Speaker

TinyOS Driver: `SpeakerDriverC`

Location: `/opt/moteiv/tos/sensorboards/invent`

| Interface      | Function                       |
|----------------|--------------------------------|
| SplitControl   | Turn on/off sensor             |
| Speaker        | Output buffer to speaker       |
| PowerControl   | Turn power on/off to speaker   |
| PowerKeepAlive | Adjust speaker shutdown policy |

#### Temperature Sensor

TinyOS Driver: `InternalTempC`

Location: `/opt/moteiv/tos/platform/msp430/adc`

| Interface                           | Function                    |
|-------------------------------------|-----------------------------|
| StdControl                          | Turn on/off sensor          |
| ADC as <code>InternalTempADC</code> | Read temperature value      |
| ADCSingle                           | Advanced ADC read interface |
| ADCMultiple                         | Advanced ADC read interface |

#### Voltage Sensor

TinyOS Driver: `VoltageC`

Location: `/opt/moteiv/tinyos-1.x/tos/system`

| Interface                   | Function                   |
|-----------------------------|----------------------------|
| StdControl                  | Turn on/off sensor         |
| ADC as <code>Voltage</code> | Read voltage value (in mV) |

## Communications

Moteiv's communication system includes three main components: a Multihop mesh networking protocol, a network duty cycling protocol, and the recently proposed "Sensornet Protocol" (SP) abstraction for sending and receiving messages. All of these protocols are used in Moteiv's mesh networking application, Delta. The source code for Delta is located in `/opt/moteiv/apps/Delta`.

### Multihop Networking

Moteiv's on-demand ad-hoc networking utilizes spatial and temporal redundancy to reliably deliver messages across a network to their destination. To use the Multihop library in an application, first include Multihop in your configuration:

```
components Multihop;
```

Then wire your application to the appropriate message handlers for your message type. For example, in your configuration:

```
AppM.Send -> MultiHop.Send[APP_ID];
AppM.Receive -> MultiHop.Receive[APP_ID];
```

Where `APP_ID` is a unique 8-bit identifier for your service or application defined in a header file. Please see the documentation for details of using the `send` interface in Moteiv's API documentation available at `/opt/moteiv/docs/nesdoc`

Messages are submitted to the Multihop service and queued until there is an opportunity to route the message towards the destination. After a message is successfully sent, an event (`Send.sendDone()`) is fired to your service notifying you that it is now safe to use the message buffer for other purposes.

### Low Power Operation

Moteiv's software includes a synchronization protocol for low power wireless network. The network duty cycling approaches uses SP (described below) for establishing and maintaining a schedule whereby the entire network wakes up together and then returns to sleep.

Including Moteiv's network duty cycling is as simple as adding a single parameter to the compilation command. Simply add the `lowpower` keyword after the compilation platform. For example:

```
make tmoteinvent lowpower
```

Try the low power networking by using Delta, the mesh networking data collection application, with the `lowpower` option:

```
cd /opt/moteiv/apps/Delta
make tmoteinvent lowpower
```

Be aware that bandwidth is very limited in low power mode (each node is only awake for a few milliseconds every two seconds). The initial synchronization of the network may require up to 15 minutes to stabilize, but will reliably report data after the initial setup phase. *Please be patient!*

Information about Moteiv's network duty cycling is included in the API documentation for the `NetSyncC` and `NetWakeC` components. The source is at `/opt/moteiv/tos/lib/netsync`; however we strongly recommend that only the most advanced users consider modifying this code. Please note that Moteiv does not support any modifications to our source.

### Sensornet Protocol (SP)

SP is a unifying link abstraction for running network protocols over a variety of link layer and physical layer technologies without changing network protocol implementation. SP is implemented by the `SPC` component.

`SPC` and its interfaces are described in detail in the following publication:  
 A Unifying Link Abstraction for Wireless Sensor Networks  
 In Proceedings of the Third ACM Conference on Embedded Networked Sensor Systems (SenSys), November 2-4, 2005.  
<http://www.polastre.com/papers/sensys05-sp.pdf>

Messages are transmitted using the `SPSend` interface and message futures are handled through the `SPSendNext` interface. To send a message on a particular AM type, such as AM type 5, wire your network protocol to `SPSend[5]`. The SP message pool will hold on to a message and its corresponding packets until it may be sent over the channel.

Fields of each SP message (`sp_message_t`) should never be directly accessed. Instead, they can be set using the parameters of the `SPSend` interface. Reading parameters should be done through the `SPMessage` interface.

Reception is on a per packet basis (not a per message basis like `SPSend`). Packets are immediately dispatched to higher layer services based on AM type. `SPReceive` provides information about each packet, including a token that identifies which interface a message originated.

The SP Neighbor Table is accessed through the `SPNeighbor` interface. Users must wire to the SP Neighbor Table with the parameter `unique("SPNeighbor")`. Each service has its own identity for controlling the insertions, removals, and changes of entries in the SP Neighbor Table. See the `SPNeighbor` interface in the API documentation for more information.

Various utilities as part of SP's processing are available in the `SPUtil` interface. These utilities include link estimation functions and link post-arbitration time stamps.

### Useful TinyOS Components

There are many useful libraries including with Moteiv's distribution of TinyOS. Below, many of these components and their functions are listed. For additional resources, please check Moteiv's support website at <http://www.moteiv.com/support.php>. It is frequently updated with tips, techniques, and troubleshooting articles.

TinyOS Distribution Organization under the `/opt/moteiv` directory:

| Directory               | Description                          |
|-------------------------|--------------------------------------|
| apps                    | Moteiv applications                  |
| apps/invent             | Tmote Invent-specific applications   |
| doc/nesdoc              | API documentation in HTML format     |
| tos/lib                 | TinyOS libraries (SP, Multihop, etc) |
| tos/platform/tmote      | Tmote-specific platform components   |
| tos/sensorboards/invent | Tmote Invent driver components       |
| tools/java              | Moteiv mote-interface java tools     |
| tinyos-1.x              | TinyOS components used by Moteiv     |

Useful TinyOS components:

| TinyOS Component    | Function                                    |
|---------------------|---|
| BitVectorC          | Methods to manipulate vectors of bits       |
| LedsC               | Turn on or off the LEDs                     |
| MainControlC        | Start a component on boot with MainControlC |
| ObjectPoolC         | Create and manage a pool of generic objects |
| TimerMilliC         | Create a new millisecond system timer       |
| UartDetectC         | Detect if a PC is active & connected        |
| UartPresenceC       | Detect the presence of PC's USB port        |
| UserButtonC         | Enable input from User Button               |
| UserButtonAdvancedC | Advanced functionality from User Button     |

The documentation for all of these components is available within the `/opt/moteiv/doc/nesdoc` directory.

In addition to TinyOS components, there are a few useful C libraries available in `/opt/moteiv/tos/lib/util/`:

| C Library       | Function                        |
|-----------------|---------------------------------|
| circularQueue.h | A generic circular queue object |
| fft_i8.h        | 8-bit integer FFT routines      |

## Notes

## General Information

### Document History

| Revision | Date       | Notes           |
|----------|------------|-----------------|
| 1.0      | 2006/02/27 | Initial Release |

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