ARM, mbed, and the Internet of Things

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Introduction

- ARM
  - Microprocessor design company
  - More than 50 billion ARM cores have been shipped to date, with a projected 100+ billion shipped by 2020.
- mbed
  - Originally, software libraries, hardware designs and online tools for professional rapid prototyping of products based on microcontrollers from the ARM Cortex-M family.
  - Recently extended to include operating systems, services and tools to enable the development and deployment of the Internet of Things (IoT)
- Internet of Things
  - billions of interconnected devices - household appliances, medical devices, industrial controllers, automobiles, cloud servers, mobile phones etc. - offering opportunities for monitoring, control and big data analysis

Organisation of the talk

- IoT applications are complex, integrating many components:
  - hardware platforms, operating systems, software development tools, languages, middleware, applications, communication protocols, and data representations.
- Approaches to IoT are many and various; no definitive answers yet in any areas of development.
- This talk describes a simple but complete IoT system which
  - illustrates, explains and clarifies the many components and their interactions;
  - offers a “strawman” proposal – definitely not the final word.
- The talk concludes with a brief introduction to some emerging methods, protocols and standards that may become part of a more stable approach to IoT.
- Not so much ‘getting ready for the Internet of Things’ as ‘getting ready to get ready for the Internet of Things’.

IoT opportunities

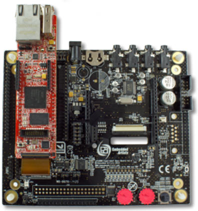
Projections for 2020, according to (Gartner, 2013) ...

- 26 billion connected devices in the IoT
- $>$ \$300 billion incremental revenue from IoT services
- growth in IoT will far exceed growth in other connected devices, e.g. the number of PCs, smartphones and tablets will reach about 7.3 billion units

Why this growth in IoT?

- ...because we want it
  - 'things' can have greater functionality and become more 'intelligent'
  - 'things' can be managed more easily
  - 'things' can provide us with more information
- ...and because we can
  - embedded chips are becoming: cheaper, smaller, lower power
  - communication is becoming faster

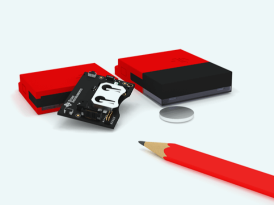
ARM Embedded Systems Education Kit (A ‘Thing’ ?)



- NXP LPC4088 QSB - 120 MHz ARM Cortex M4, Flash: 8 MB QSPI + 512 KB on-chip, RAM: 32 MB SDRAM + 96 KB on-chip SRAM + 4 KB on-chip E2PROM, 4 LEDs, push button, USB, Ethernet, RF connectors
- Experiment base board - RGB LED, joystick, accelerometer, temperature sensor, potentiometer, 4.3 inch (480x272 pixel) TFT LCD
- Total cost - approx. £95.00
- See (Embedded Artists, 2016)

Some other 'Things'

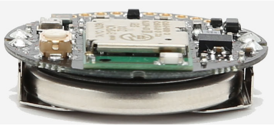
TI SensorTag



(Texas Instruments, 2015)

- 48MHz TI CC2650 SOC with ARM Cortex M3 + BLE, Zigbee, 6LoWPAN;
- Sensors: infrared and ambient temperature; ambient light; humidity; barometric pressure; 9-axis motion tracking - accelerometer, gyroscope, compass; magnetic proximity; microphone
- Cost approx. £20

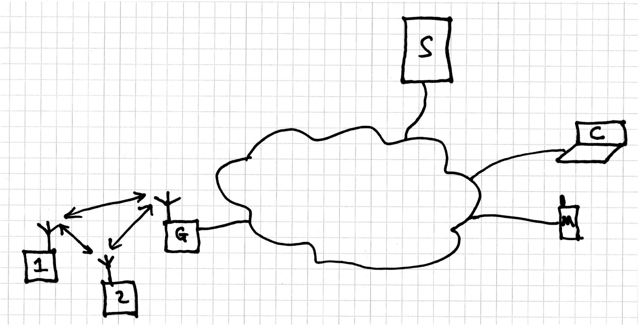
MetaWear C



(MBIENTLAB, 2016)

- Nordic nRF51822 SOC with ARM Cortex M0 CPU + BLE
- Sensors: BMI160 accelerometer + gyroscope; temperature sensor
- Cost approx. £35

Demonstration configuration



G	gateway	S	server
1	sensor node	C	computer
2	sensor node	M	mobile device

Demonstration functionality

Sensor Node

Monitor: Sample the sensors on experiment baseboard at 5 Hz

- Accelerometer [X,Y,Z]
- Potentiometer
- Temperature

Control: Accept commands via the gateway

- LEDs: turn on and off
- Display: change background colour; print message

Gateway

- Relay data from sensor nodes to server
- Relay commands from server to sensor nodes

Server

- Relay sensor node data from gateway to web clients
- Relay commands from web clients to gateway

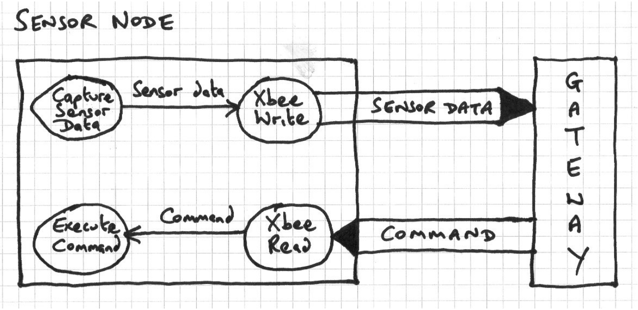
Browser

- Receive sensor node data from server; display it to user
- Receive commands from user; send to server

Demonstration

LET'S SEE A DEMONSTRATION

How it works: Sensor Node



- LPC4088QSB + Xbee ZB RF module, managing an experiment baseboard
- Running a simple, multi-tasking RTOS (uC/OS-II)
- Essentially, 4 simple uC/OS-II tasks running concurrently
- All devices handled using the mbed libraries + some extensions from Embedded Artists for the experiment baseboard.

ARM mbed (ARM Ltd., 2016a)

This refers to the 'classic' mbed. More on mbed for IoT later.

Software Development Kit (SDK)

- startup code, C runtime, libraries and peripheral APIs
- 55 platforms identified as 'mbed-enabled' on the mbed site as of May 2016
- Target vendors include NXP, Nordic, Renesas, ST, and Wiznet
- mbed code builds on the ARM Cortex Microcontroller Software Interface Standard (CMSIS)
- Most high-level mbed code written in C++, low-level code in C

Hardware Development Kit (HDK)

- provides full microcontroller sub-system design files and firmware for building development boards and custom products that benefit from the native support of the mbed SDK

Free online compiler

- a powerful online IDE with professional ARM compiler backend
- supports mbed SDK
- import and export libraries and modules to the online community
- code can be exported for use with external compilers, e.g. Keil MDK

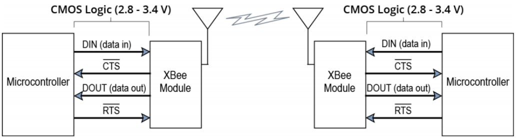
mbed blinky

```
#include "mbed.h"

DigitalOut myled(LED1);

int main() {
    while(1) {
        myled = 1;
        wait(0.2);
        myled = 0;
        wait(0.2);
    }
}
```

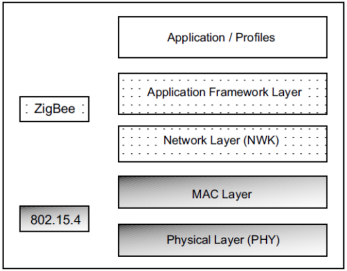
- No other code required from the application developer: startup, C runtime etc
- `DigitalOut` is a C++ class that hides most of the details of the underlying GPIO. `LED1` is a synonym for the appropriate GPIO pin number.
- Similar provision made for on-chip peripherals, e.g.: timers, I^2C, SPI, UART etc.
- Also provision for more complex peripherals, e.g.: Ethernet, CAN etc.
- Compliance with CMSIS ensures code is portable between toolchains
- No problem integrating mbed SDK with an RTOS such as uC/OS-II

Xbee ZB RF module

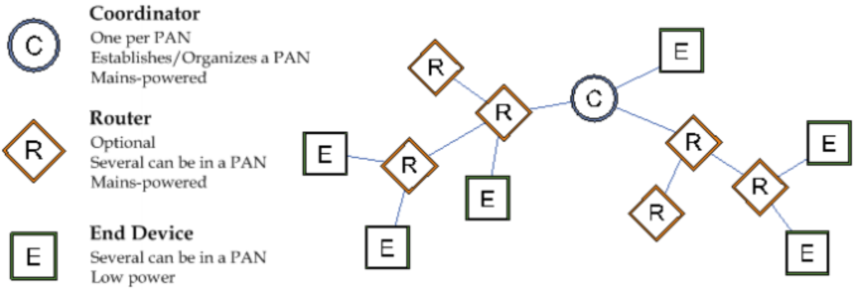
- RF module by Digi International – ISM 2.4 GHz band
- Range: up to 40 m indoors/urban; up to 120 m outdoor line-of-sight
- Low power: TX peak current and RX current 40 mA (@3.3V); power down current $< 1\mu A$
- Implements ZigBee for wireless mesh networking (WPAN), see (ZigBee Alliance, 2016)
- Data throughput: variable, from 35 kb/s to 5 kb/s



(Digi International, 2015)



ZibBee Network



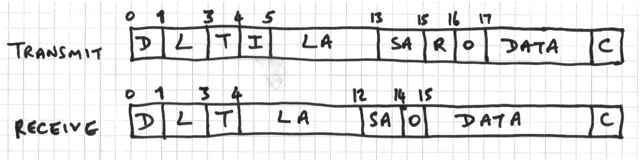
(Digi International, 2015)

Data Format

Sensor data is represented simply using JSON, e.g.


```
{
  "type":"DATA","id":"SN01","ax":1,"ay":2,"az":24,
  "pt":58,"tm":24.2
}
```


It's packed into an Xbee transmit frame and received at the gateway in a receive frame:



D – Delimiter (0x7E), L – Length, T – Frame type (0x10 Transmit, 0x90 Receive), I – Identifier, LA – Long address, SA – Short address, R – Broadcast radius, O – Options, DATA – JSON DATA, C – Checksum

How it works: Gateway

- Hardware:
  - Raspberry Pi Model B (revision 0002), single-core 700 MHz BCM2835, 256 MB RAM + Xbee ZB RF Module + WiFi dongle
- Software:
  - PyPy (PyPy, 2016)
    - fast Python implementation with JIT compiler
  - Twisted (Twisted Matrix Labs, 2016)
    - open source, event-driven networking engine written in Python
  - Autobahn|Python (Tavendo GmbH, 2015)
    - high-performance, fully asynchronous, scalable implementation of Websockets
- Implementation:
  - Asynchronously receive RF data via serial link; when a complete frame is received, extract the JSON data and send it to the server via a websocket
  - Receive commands from the server via a websocket and send via the serial link to RF module for transmission to the sensor node.

The Websocket Protocol

- provides a bi-directional communication channel over a single TCP connection
- the initiating handshake is an HTTP Upgrade request
- once the upgrade occurs, HTTP is no longer involved – message-based protocol over TCP
- typically uses port 80 (`ws://myserver.com/`) or port 443 `wss://myserver.com/` for a secure channel)
- allows a server to *push* data to a browser, and the browser to send requests to the server without requiring multiple HTTP connections, reloading or polling
- So your browser can display *current information* efficiently
- supported by most major modern browsers: Firefox, Google Chrome, Safari, Internet Explorer, Opera.
- can also be used by applications outside the browser
- defined in RFC6455 (Fette and Melnikov, 2011)

Simple Websocket Client

```
class MyClientProtocol(WebSocketClientProtocol):

    def onOpen(self):
        self.sendMessage(u"Hello, world!".encode("utf8"))

    def onMessage(self, payload, isBinary):
        if isBinary:
            print("Binary message received: {0} bytes".format(
                                                  len(payload)))
        else:
            print("Text message received: {0}".format(
                                  payload.decode("utf8")))
```

- runs in an event loop provided by the Twisted framework
- on a websocket open event, the `onOpen()` method runs
- on a websocket message received event, the `onMessage()` method runs

How it works: Server

- Hardware:
  - HP ProLiant DL320e Gen8, Quad core Intel Xeon CPU E3-1220 V2 @ 3.10GHz, 8 GB RAM
- Software:
  - Tornado (The Tornado Authors, 2016)
    - a Python web framework and asynchronous networking library
    - by using non-blocking network I/O, Tornado can scale to tens of thousands of open connections
- Implementation:
  - Accepts websocket connection requests from gateways and from web clients (browsers)
  - Acts as a publish/subscribe broker
    - Gateways act as publishers of sensor data
    - Browsers act as subscribers to ‘topics’ – data from some particular sensor node
    - Topics are identified by sensor node id, e.g. `SN01`, i.e. when you subscribe to data from a sensor node, you subscribe to *all* its data, you can’t choose just the temperature data, for example

Data structure for a primitive publish/subscribe broker

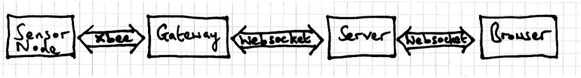
```
topics = {
  "SN00" : {
    "publisher" : <websocket gateway1>,
    "subscribers" : [
      <websocket pc1>,
      <websocket mobile1>
      <websocket tablet1>
    ]
  },
  "SN01" : {
    "publisher" : <websocket gateway1>,
    "subscribers" : [
      <websocket pc1>,
      <websocket mobile2>
    ]
  }
  "SN02" : {
    "publisher" : <websocket gateway2>,
    "subscribers" : [
      <websocket pc1>,
      <websocket tablet2>
    ]
  }
}
```

How it works: Browser

- Hardware:
  - Anything that can run a modern browser . . .
- Software:
  - Any modern browser, supporting websockets, e.g. Google Chrome, Firefox, Safari, Internet Explorer etc.
  - Javascript libraries:
    - Smoothie Charts for accelerometer data
    - JustGage for generating gauges: potentiometer, temperature
  - Bootstrap for responsive web page
- Implementation:
  - Loads page and libraries
  - Creates chart and gauges
  - Opens websocket to server
  - Extracts sensor node id from URL and sends a SUBSCRIBE message to the server
  - Implements an `onmessage()` function that receives PUBLISHed data for the sensor node and updates the chart and gauges accordingly.
  - Implements various functions to send COMMANDs to the server

Moving on: Security

Don't be the next Nissan Leaf (Hunt, 2016) !!!



- Sensor node to gateway (Xbee)
  - 128 bit AES encryption
  - Two security keys (network and link) that can be preconfigured or obtained during joining
  - Support for a trust centre (usually the coordinator)
  - Provision to ensure message integrity, authentication and confidentiality
- Gateway to server and server to browser (websocket)
  - Use the `wss://myserver.com` form of the protocol, which ensures that data is encrypted and sent using TLS.
  - Don't tunnel arbitrary TCP services over a websocket (vulnerable to cross-site scripting attack)
  - Validate client (browser) input, e.g. server may be vulnerable to SQL injection attack over websocket just as over TCP
  - Validate server data – treat as data, don't evaluate as code
  - Need client authentication/authorisation mechanism – 'ticket'-based protocol?

Moving on: data protocols

- MQTT
  - binary protocol for publish/subscribe architectures
  - lightweight, efficient, simple to implement, minimal packet overhead
  - developed by IBM and Arcom in 1999 for connecting oil pipelines over satellite links
  - Typically runs over TCP and TLS
  - OASIS standard (Banks and Gupta, 2014)
- CoAP – Constrained Application Protocol
  - specialized web transfer protocol for use with constrained nodes and constrained networks in the Internet of Things
  - based on the REST model: Servers make resources available under a URL, and clients access these resources using methods such as GET, PUT, POST, and DELETE.
  - Runs over UDP and DTLS
  - open standard RFC7252 (Shelby et al., 2014)

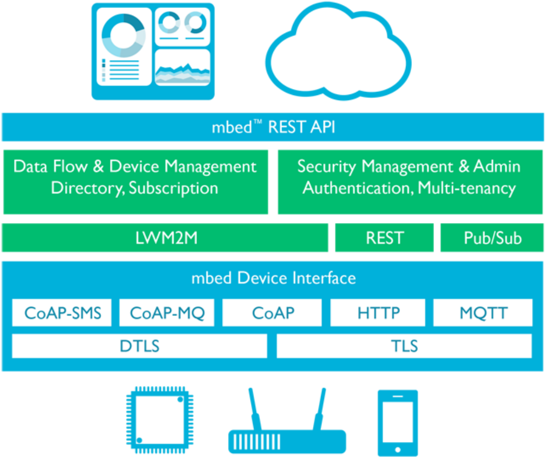
Design options I

- IP or not for communication at the sensor node (collapse the gateway into the node)?
  - 6LoWPAN – IPv6 over Low-power Wireless Personal Area Networks (802.15.4)
- What about the application and transport layers?
  - MQTT over TCP
  - CoAP over UDP
- What about the sensor node OS?
  - Lightweight threads, e.g. (Contiki, 2016) and (Riot, 2016)
    - Both open-source and support protocols such as IPv6, 6LoWPAN and CoAP
  - Event-driven, asynchronous scheduler e.g. (mbed OS, 2016)

Design options II

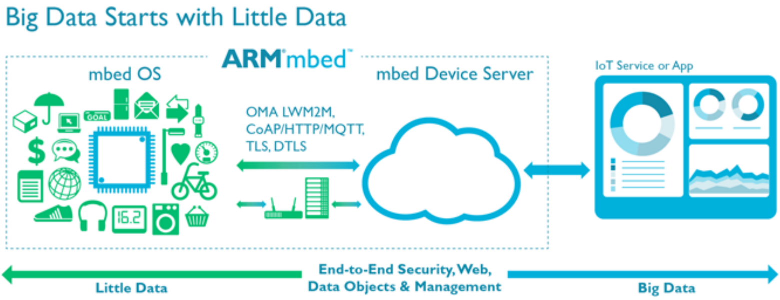
- What about the server?
  - Roll your own using `Node.js` instead of Python ?!
    - Another event-driven, non-blocking I/O framework but for Javascript (in the server!)
  - Host an MQTT broker, e.g. Mosquitto (Eclipse, 2016a) and Mosca (Collina, 2016)
  - Use a cloud service, e.g.
    - ARM device server (ARM Ltd., 2016d)
    - IBM Watson Internet of Things (IBM, 2016)
    - many others . . .
- and the clients?
  - Talking to the browser
    - HTTP – REST
    - Websocket – MQTT Javascript client, e.g. Eclipse Paho
  - Talking to the sensor nodes
    - MQTT embedded client (supported by mbed), e.g. Eclipse Paho

ARM device server



(ARM Ltd., 2016d)

The ARM IoT Vision



(ARM Ltd., 2016c)

QUESTIONS?

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