ECEN 5823-001 / -001B

Internet of Things Embedded Firmware

Lecture #5

12 September 2017

Be Boulder.

University of Colorado Boulder

Agenda

- Class announcements
- Office Hours
- Review of Simplicity Exercise – Will postpone to Tuesday the 12th
- Managing Energy Modes Assignment
  - Objective: Become more familiar with the Silicon Labs' Simplicity development system as well as learn the different Blue Gecko energy modes and how to manage them.
- Documentation style sheet
- Interrupts
- LETIMER0
- Wireless Networks - Infrastructure

Class Announcements

- Quiz #3 is due at 11:59pm on Sunday, September 17th, 2017
- Managing Energy Mode Assignment is due at 11:59pm on Wednesday, September 13th, 2017

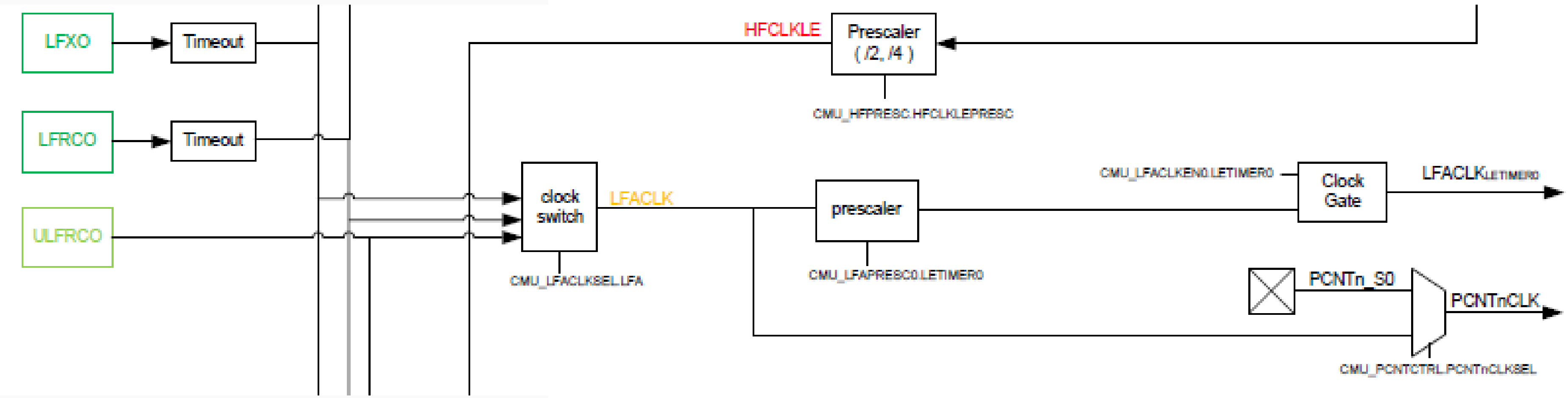
Note on peripherals that can have multiple copies in the MCU

- A peripheral is indicated as possibly having multiple copies by suffix “n”
  - LETIMERn
  - ACMPn
  - Etc.
- For C-code that points directly to the desired register of the copy that is programming to, the “n” must be replaced by the peripheral number
  - LETIMER0 or LETIMER1
  - ACMP0 or ACMP1
  - Void ACMP0_IRQHandler(void);
- But, the bits in the register are defined by the peripheral name only, no “n” required
  - LETIMER_IFC_UF
  - ACMP_STATUS_ACMPOUT

Quiz 2 review

Which clock sources can the LETIMER0 use in EM0?

- [x] ULFRCO
- [x] LFRCO
- [ ] HFXO
- [x] LFXO
- [ ] HFRCO



Quiz 2 review

21.5.2 LETIMERn_CMD - Command Register

Offset	Bit Position																														
0x004	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Reset																												0	0	0	0	0
Access																												W1	W1	W1	W1	W1
Name																												CTO1	CTO0	CLEAR	STOP	START

Bit	Name	Reset	Access	Description
31:5	*Reserved*	*To ensure compatibility with future devices, always write bits to 0. More information in 1.2 Conventions*		
4	CTO1	0	W1	**Clear Toggle Output 1** Set to drive toggle output 1 to its idle value
3	CTO0	0	W1	**Clear Toggle Output 0** Set to drive toggle output 0 to its idle value
2	CLEAR	0	W1	**Clear LETIMER** Set to clear LETIMER
1	STOP	0	W1	**Stop LETIMER** Set to stop LETIMER
0	START	0	W1	**Start LETIMER** Set to start LETIMER

Quiz 2 review

Access Type

The register access types used in the register descriptions are explained in Table 1.1 Register Access Types on page 2.

Table 1.1. Register Access Types

Access Type	Description
R	Read only. Writes are ignored
RW	Readable and writable
RW1	Readable and writable. Only writes to 1 have effect
(R)W1	Sometimes readable. Only writes to 1 have effect. Currently only used for IFC registers (see 3.3.1.2 IFC Read-clear Operation)
W1	Read value undefined. Only writes to 1 have effect
W	Write only. Read value undefined.
RWH	Readable, writable, and updated by hardware
RW(nB), RWH(nB), etc.	"(nB)" suffix indicates that register explicitly does not support peripheral bit set or clear (see 4.2.2 Peripheral Bit Set and Clear)
RW(a), R(a), etc.	"(a)" suffix indicates that register has actionable reads (see 7.3.6 Debugger reads of actionable registers)

Quiz 2 review

Complete the below C line of code to start LETIMER0 by writing directly to its register.

```
LETIMER0->CMD = LETIMER_CMD_START;
```

Quiz 2 review

21.5.11 LETIMERn_IFC - Interrupt Flag Clear Register

Offset	Bit Position																															
0x028	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
Reset																												0	0	0	0	0
Access																												(R)W1	(R)W1	(R)W1	(R)W1	(R)W1
Name																												REP1	REP0	UF	COMP1	COMP0

Bit	Name	Reset	Access	Description
31:5	*Reserved*	*To ensure compatibility with future devices, always write bits to 0. More information in 1.2 Conventions*		
4	REP1	0	(R)W1	**Clear REP1 Interrupt Flag** Write 1 to clear the REP1 interrupt flag. Reading returns the value of the IF and clears the corresponding interrupt flags (This feature must be enabled globally in MSC.).
3	REP0	0	(R)W1	**Clear REP0 Interrupt Flag** Write 1 to clear the REP0 interrupt flag. Reading returns the value of the IF and clears the corresponding interrupt flags (This feature must be enabled globally in MSC.).
2	UF	0	(R)W1	**Clear UF Interrupt Flag** Write 1 to clear the UF interrupt flag. Reading returns the value of the IF and clears the corresponding interrupt flags (This feature must be enabled globally in MSC.).
1	COMP1	0	(R)W1	**Clear COMP1 Interrupt Flag** Write 1 to clear the COMP1 interrupt flag. Reading returns the value of the IF and clears the corresponding interrupt flags (This feature must be enabled globally in MSC.).
0	COMP0	0	(R)W1	**Clear COMP0 Interrupt Flag** Write 1 to clear the COMP0 interrupt flag. Reading returns the value of the IF and clears the corresponding interrupt flags (This feature must be enabled globally in MSC.).

Quiz 2 review

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Quiz 2 review

Complete the C line of code to clear the UF interrupt bit.

(LETIMER0->IFC, LETIMER0 -> IFC) = LETIMER_IFC_UF;

Quiz 2 review

Select all the C lines of code that would enable the LFXO oscillator to this Write Only register.

- ✓ `CMU->OSCENCMD = CMU_OSCENCMD_LFXOEN;`
- ✗ `CMU->OSCENCMD = CMU->OSCENCMD + CMU_OSCENCMD_LFXOEN;`
- ✗ `CMU->OSCENCMD |= LFXOEN;`
- ✓ `CMU_OscillatorEnable(cmuOsc_LFXO, true, true);`

Quiz 2 review

Instead of _, it should be ->

Select all the C lines of code that would just disable the LETIMER0 underflow interrupt.

```
LETIMER0_IEN = LETIMER0->IEN & ~LETIMER_IEN_UF;
```

Should be &= to AND with the UF mask

```
LETIMER0->IEN = ~LETIMER_IEN_UF;
```

```
LETIMER0->IEN &= ~LETIMER_IEN_UF;
```

```
LETIMER_IntDisable(LETIMER0, LETIMER_IEN_UF);
```

Quiz 2 review

Order the following pseudo code for a generic non-nested interrupt handler routine.

2	Interrupt flag variable = source interrupt register
4	interrupt handling routine
5	re-enable interrupts
1	disable all interrupts
3	clear cause of source interrupt

Quiz 2 review

Match the following sleep calls to the appropriate function or interrupt type handler

1	A call to a peripheral
2	A routine to turn off an peripheral
3	Interrupt handler of a "re-occurring" peripheral
2	Interrupt handler of a "single operation" peripheral

1. blockSleepMode(EMx);
2. unblockSleepMode(EMx);
3. nothing

Quiz 2 review

Using the below information from the Energy Profiler, order the devices from lowest average energy / current to the most. The below information is for a period, and all of the periods repeat indefinitely.

Period is indefinite

- Continuous at 21uA

Period of repetition is 4.5s

- In EM3 at 1uA for 4.45s
- In EM0 at 3.1mA for 0.005s
- In EM1 at 1.4mA for 0.045s

Period of repetition is 5s

- In EM3 at 1uA for 4.995s
- In EM0 at 3.1mA for 0.005s

Period of repletion is 0.10S

- In EM2 at 1.4uA for 0.098s
- In EM2 at 87.0uA for 0.002s

Quiz 2 review

Using the below information from the Energy Profiler, order the devices from lowest average energy / current to the most. The below information is for a period, and all of the periods repeat indefinitely.

Period of repetition is 4s

- In EM3 at 1uA for 3.995s

- In EM0 at 3.1mA for 0.005s

Period is indefinite

- Continuous at 5uA

Period of repetition is 3.5s

- In EM3 at 1uA for 3.45s

- In EM0 at 3.1mA for 0.005s

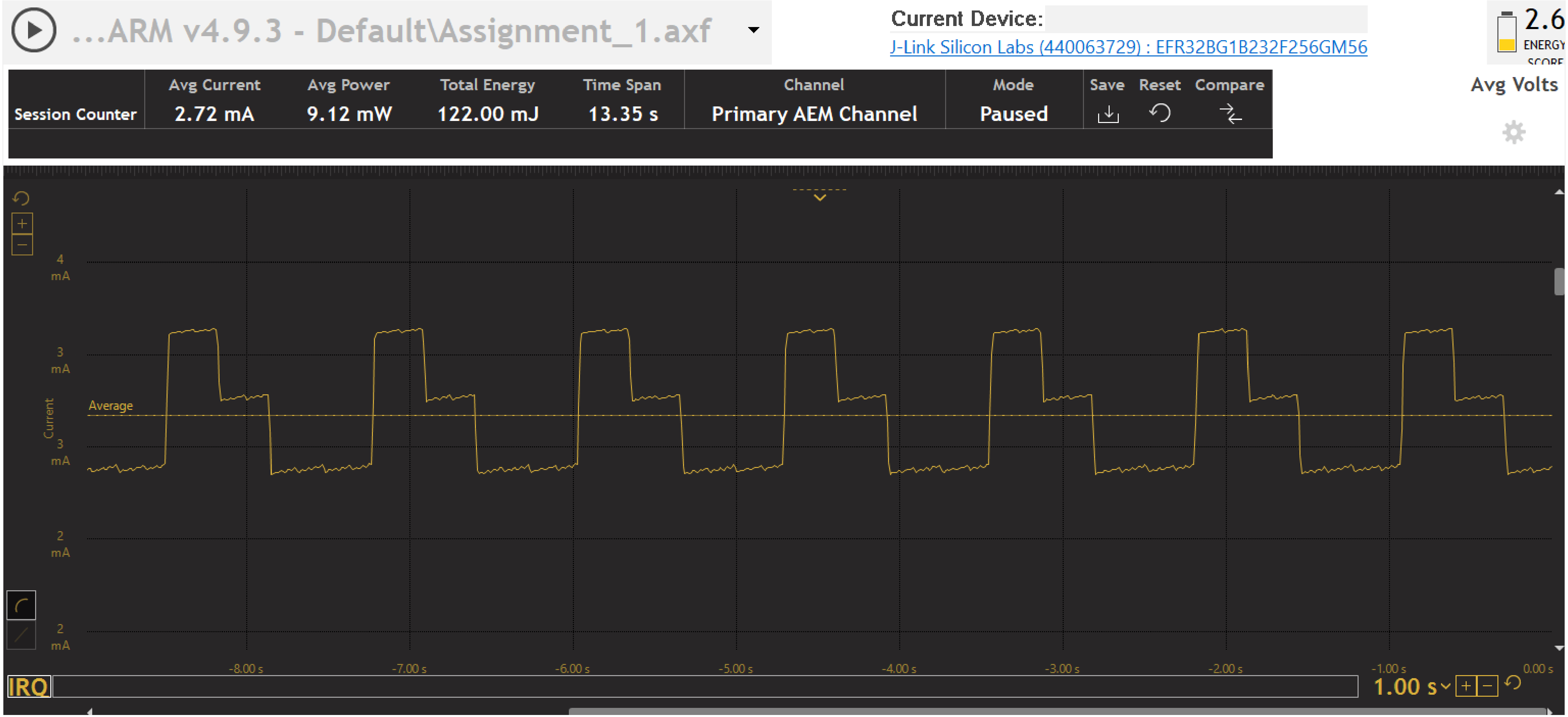
- In EM1 at 1.4mA for 0.045s

Period of repletion is 0.20S

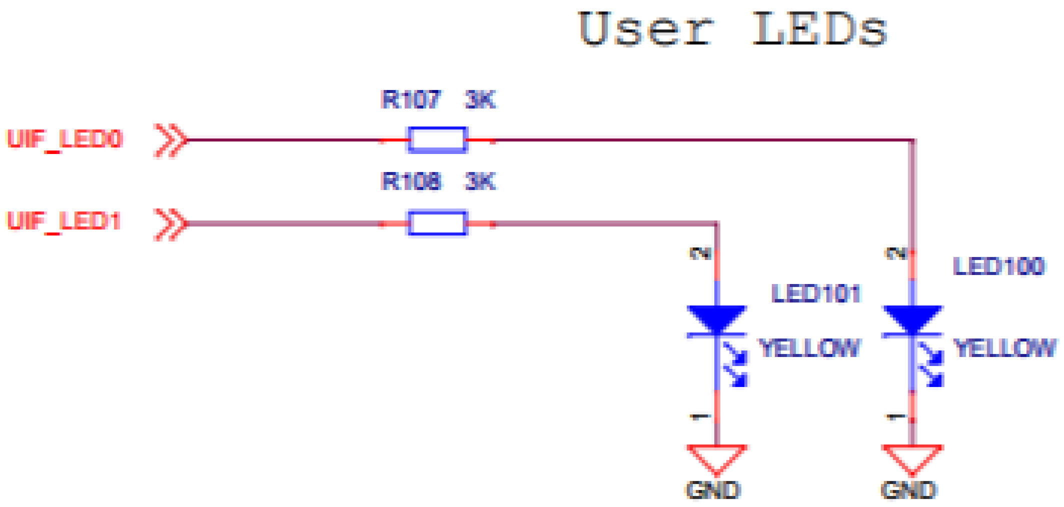
- In EM2 at 1.4uA for 0.198s

- In EM2 at 87.0uA for 0.002s

Simplicity Exercise Review



LED0 current required?



D Electrical & Optical Properties:

Properties	Test conditions		Value			Unit
			min.	typ.	max.	
Peak Wavelength	20 mA	λ_{Peak}		595		nm
Dominant wavelength	20 mA	λ_{Dom}		590		nm
Luminous Intensity	20 mA	I_V	90	120		mcd
Forward Voltage	20 mA	V_F		2.0	2.4	V
Spectral Bandwidth	20 mA	$\Delta\lambda$		15		nm
Reverse Current	5 V	I_{Rev}			10	µA
Viewing Angle	20 mA	$2\theta_{50\%}$		140		°

Simplicity Exercise

1. Using the Energy Profiler, what is the instantaneous current measured once the program has begun without any modification to the sample code?
    a. 4.90 – 5.40mA
2. What is the Energy Score after resetting the Energy Profiler and waiting 30 seconds without any modification to the sample code?
    a. 2.3
3. After commenting out the code to toggle LED1, what is the instantaneous current measured while LED0 is off?
    a. 4.40 – 4.95mA
4. After commenting out the code to toggle LED1, what is the instantaneous current measured while LED0 is on?
    a. 4.85 – 5.55mA
5. After commenting out the code to toggle LED1, what is the Energy Score after resetting the Energy Profiler and waiting 30 seconds?
    a. 2.3

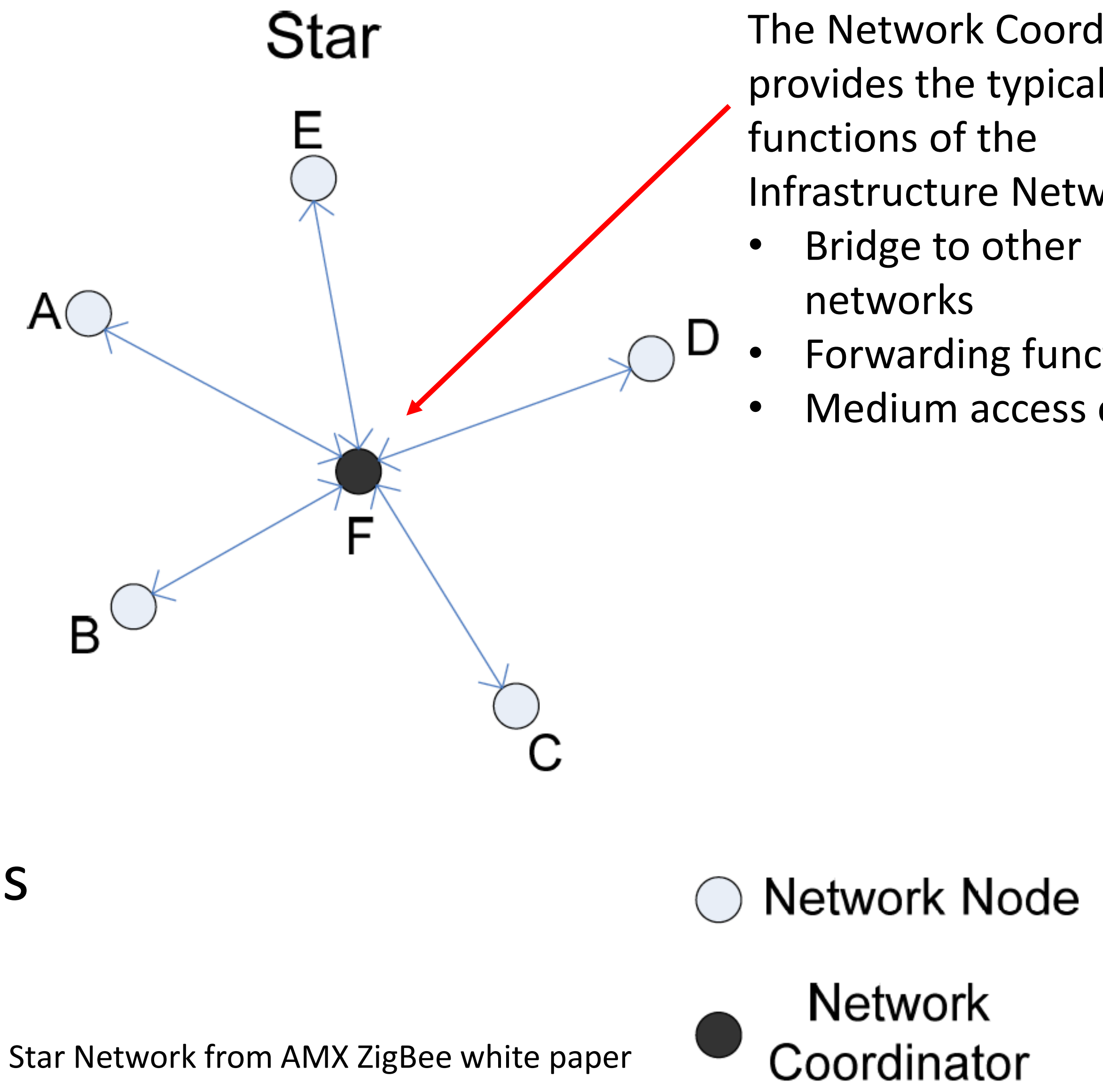
HFXO Autostart function

- `CMU_HFXOAutostartEnable(0, false, false);// HFXO auto start must be disabled before switching to HFRCO`
- `CMU_ClockSelectSet(cmuClock_HF, cmuSelect_HFRCO);`
- `CMU_OscillatorEnable(cmuOsc_HFXO, false, false);// Disable HFXO to save energy after HFRCO has been enabled`

https://www.youtube.com/watch?v=fNL7d_fbHKQ

Wireless Networks

- Infrastructure networks provide typically these functions
  - Bridge to other networks
  - Forwarding functions
  - Medium access control
- In Infrastructure Networks, communications typically goes from wireless nodes to a wireless access point
  - Star Network



Star Network from AMX ZigBee white paper

The Network Coordinator provides the typical functions of the Infrastructure Network

- Bridge to other networks
- Forwarding functions
- Medium access control

Infrastructure Networks

- These networks are simpler due to the network functions are placed into the access point and the wireless clients can remain quite simple
- Collisions may occur if the medium access of the wireless nodes and the access point is not coordinated.
  - With the Access Point controlling medium access, no or very little collisions are possible
  - A useful feature for maintaining and controlling Quality of Service (QoS)
- Infrastructure wireless networks lose some of the flexibility of wireless networks due to their reliance on the infrastructure.
  - Single Point of failure
  - Cannot be set up quickly – infrastructure must be in place

WiFi is an example of a Infrastructure Network

- Access point is required to coordinate medium access
- Access point to bridge to other networks
- Access point to forward packets upstream and downstream
- Coordinates Quality of Service
  - Audio
  - Video
  - Games, etc.
- Star Network
  - Wireless clients cannot communicate with each other directly

Wireless LAN advantages:

- Flexibility
  - Within radio range coverage, nodes can communicate without further restriction
  - Radio waves can penetrate walls, senders and receivers can be placed anywhere within radio coverage
- Design
  - Wireless networks allow for the design of small, independent devices
  - Cables not only restrict users access to the network, but to the physical design of the device
- Robustness
  - Wireless networks can survive disasters such as a cellular network providing services while the wired network of a building is down
- Cost
  - After the cost of installing an access point, adding additional users does not increase the cost

Wireless LAN disadvantages

- Quality of Service
  - Typically WLANs offer lower quality than their wired counterparts due to lower bandwidth limitations of radio transmissions
- Restrictions
  - All wireless products have to comply with national and potentially international regulations
- Safety and Security
  - Radio waves for data transmission may interfere with other high-tech equipment in hospitals or radar installations
  - Open radio interfaces make eavesdropping much easier than wired LAN such as fiber optics

Wireless LAN design goals

- Global operations
  - Mobile product can be taken from one country to another and should be made to operate legally in each country
- Low Power
  - WLAN clients are typically mobile and run on batteries. The WLAN design should take into account the requirements of low power devices
- License-free operation
  - WLAN operators do not want to apply for a license to use their equipment
- Robust transmission technology
  - Radios must be able to operate in potentially “noisy” RF environments such in a home with a hairdryer, vacuum cleaner, or RF obstacle

Wireless LAN design goals (continued)

- Simplified spontaneous cooperation
  - Should not require complicated setup routines, but should operate spontaneously after power-up
- Easy to use
  - These WLANs should not require complex management, but rather work in a "plug-and-play" concept
- Protection of investment
  - Huge investment has been made into wired LAN for performance, reliability, and security
  - Wireless LANs should protect this investment by bridging their wireless networks onto the wired networks

Wireless LAN design goals (continued)

- Safety and Security
  - Wireless products should have radios that are safe to be used with people and sensitive equipment
  - Encryption mechanisms should be integrated into the wireless network to provide privacy of data
- Transparency for applications
  - Existing applications should work in both wired and wireless LAN environments
  - In the wireless LAN environment, there could be higher latency and lower bandwidth available to the application

Ad-hoc networks

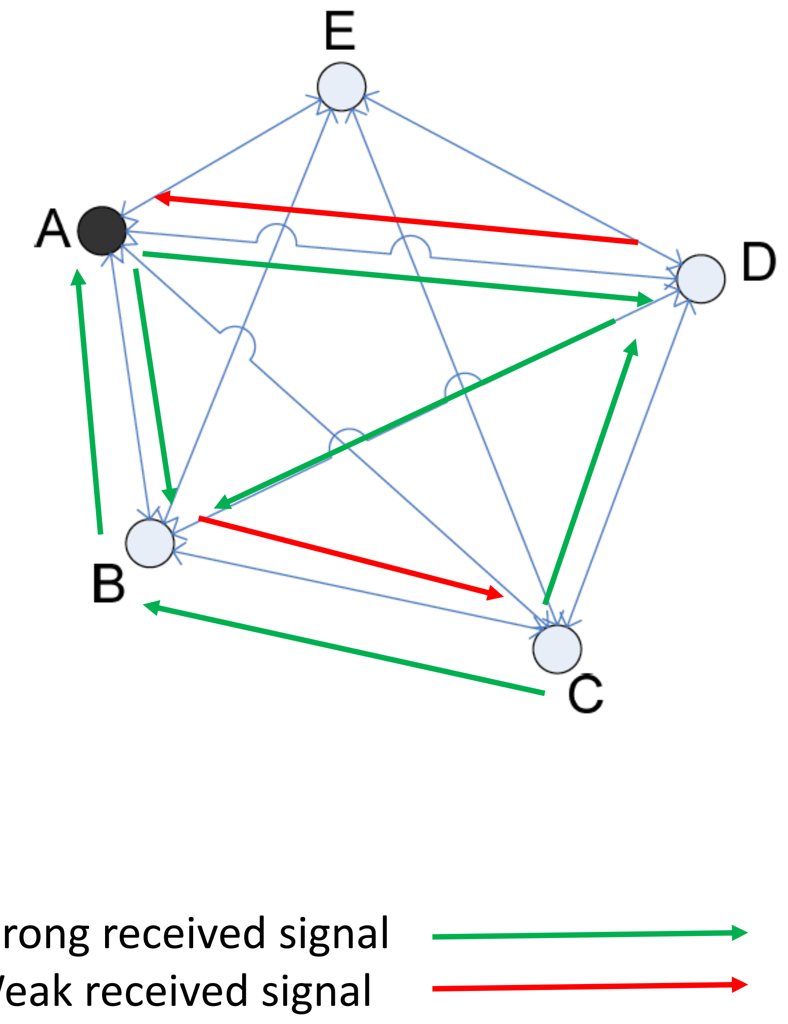
- Networks that are usually wireless that have no infrastructure to control medium access or bridge to other networks
- Examples of ad-hoc networks:
  - Instant infrastructure: Unplanned meetings or social gatherings that create a mobile network. No time to install an infrastructure environment.
  - Disaster relief: Infrastructures typically break down in disaster areas. Emergency crews can only rely on infrastructure that they can set up themselves.
  - Remote areas: Sparsely populated areas could be too expensive to extend infrastructure networks. Ad-hoc may be an appropriate cost alternative.
  - Effectiveness: For systems that regular transmit small amount of data, a connection oriented service such as cellular may be too expensive compare an application specific ad-hoc network.

Ad-hoc routing

- In a cellular or WiFi network, a base station/access point can always reach all wireless nodes, but this is not the case in an ad-hoc network
    - The star network enables the base station/access point to obtain and forward the information to all nodes as well as to send upstream or downstream
- Routing is required to find a path between the source and destination nodes as well as to forward packets
    - Due to the nodes in the ad-hoc network, one node may receive a strong signal from a particular node, but transmits a weak signal to this node. This can create a transmit path to a destination note that is different than the receive path
        - Reasons can be different antenna characteristics, transmit power.

Ad-hoc routing

- Node A is sending data to Node D
  - Since A can transmits data with a strong signal to Node D, the data will be transmitted directly from Node A to D
- Node D is responding to Node A's request by sending back the requested data
  - Since Node A receives a weak signal from Node D, the return path from Node D to Node A will be Node D-B-A



Mesh Network from AMX ZigBee white paper

Difference between wired and ad-hoc networks related to routing

- Asymmetric links: Routing information for one direction may not be appropriate for the return path.
- Redundant links: Wired links will have some redundancy built into them, but it becomes costly as the amount of redundancy increases. In an ad-hoc mesh network, redundancy can be as extreme as all of the nodes are capable of transmitting and receiving to each other.
- Interference: Wired networks have limited potential of interference, but the RF characteristics of an ad-hoc network can change as other wireless devices come into its RF range, the transmittal of other nodes in the ad-hoc network, weather conditions, etc.
- Dynamic topology: In a mobile ad-hoc network, the nodes may move that result in an ever changing routing table.

Ad-hoc routing observations to wired networks

- Traditional wired network routing algorithms converge too slowly or fail completely for a highly dynamic topology, asymmetric links, and interference
- Routing in wireless ad-hoc networks requires lower networking layer data concerning connectivity or interference can help routing algorithms find a good path
- Centralized approaches take too long collect all the nodes status and disseminate it again in a highly dynamic topology and interference
- Routing algorithms need to consider the limited battery power of these wireless nodes
- Notions that nodes of a connection with certain characteristics cannot work properly as the topology changes. Nodes to have make local decisions for forwarding packets roughly to its destination
- Need to insure that as a packet is looking for its destination does not flood the ad-hoc network and make it unusable. A hop counter is used to limit the maximum number of hops a packet can make

Thread Network example

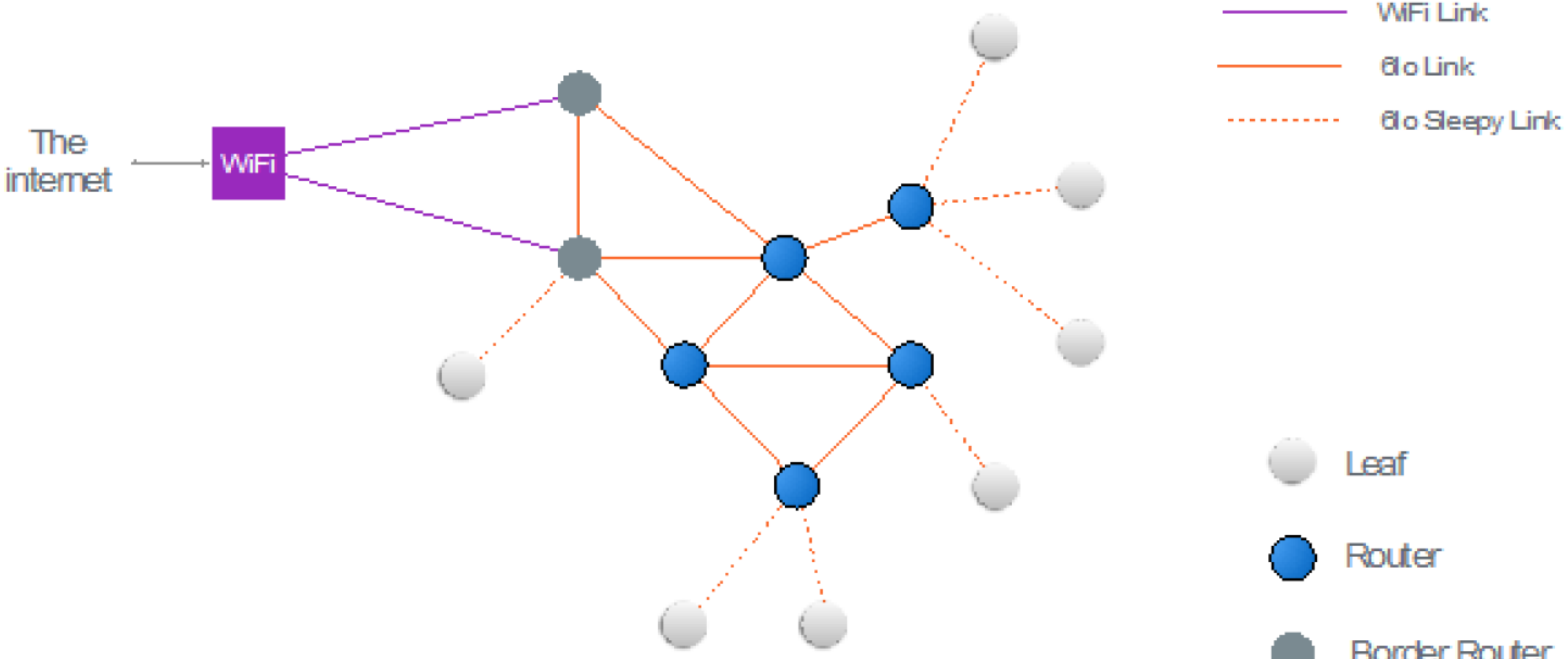


Figure 3. Basic Thread Network Topology and Devices

Thread Route and Discovery

- Thread does not use on-demand route discovery due to on-demand route discovery is costly in terms of network overhead and bandwidth due to route discovery requests flooding the network.
- All Thread Routers periodically exchange single-hop MLE advertisement packets containing link cost information to all neighbor Routers, and path costs to all other Routers in the Thread Network. These periodic, local updates provide all Routers up-to-date path cost information to any other Router in the network. If a route is no longer usable, Routers can make a selection on the next most suitable route to the destination. This self-healing routing mechanism allows Routers to quickly detect when other Routers have dropped off the network, and calculate the best path to maintain connectivity to all other devices in the Thread Network.

Thread Route and Discovery (continued)

- The link cost in a thread network is based on the link quality of incoming neighboring devices. The link cost is a measure of the Received Signal Strength Indicator (RSSI) of received messages above the receive level.

Table 1 summarizes the link quality and link cost.

Table 1. Link Quality and Link Cost

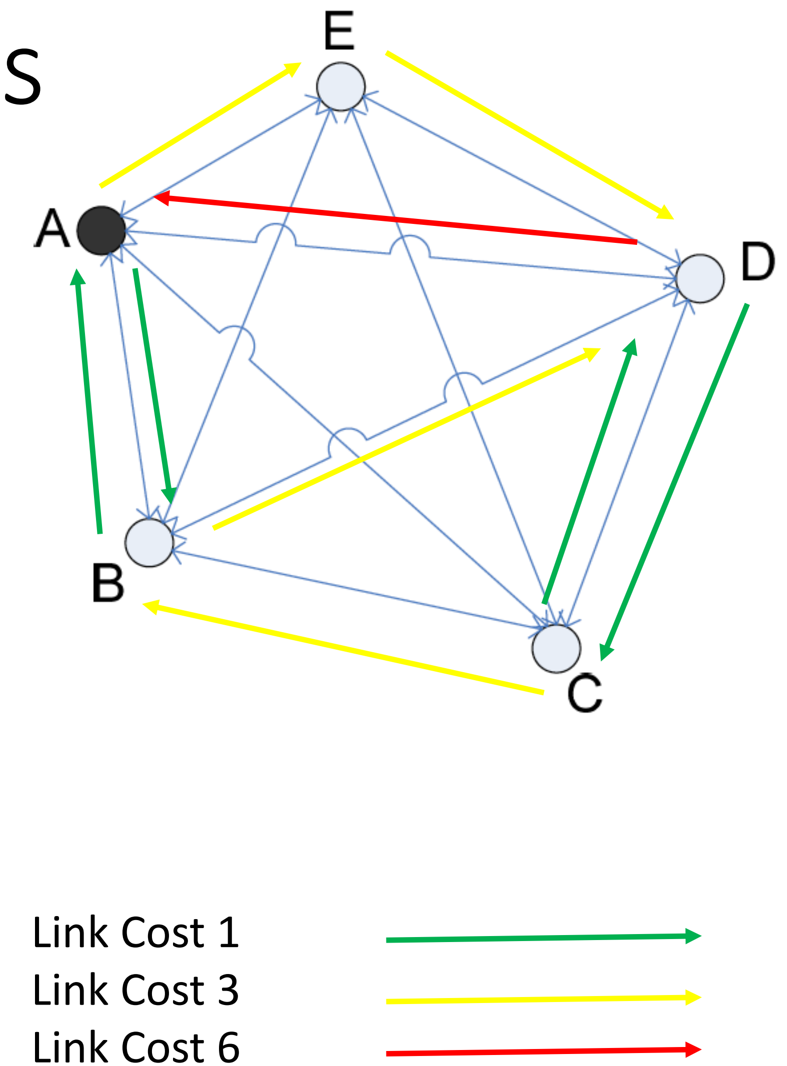
Link Quality	Link Cost
0	unknown
1	6
2	2
3	1

Thread Route and Discovery (continued)

- The path cost to any other node in the Thread Network is then the minimum sum of link cost to reach that node.
- Routers monitor these costs, even as the radio link quality or topology of the network changes, and propagate the new costs through the Thread Network using the periodic MLE advertisement messages.
- Routing cost is based on bi-directional link quality between two devices.

Thread Link and Route costs

- What is the Path Cost from A to D?
  - A-E (3) + E-D(3) = 6
  - A-B (1) + B-D(3) = 4 ✓
- What is the Route Cost from A to D?
  - D-C (1) + C-B (3) + B-A (1) = 5 ✓
  - D-A (6) = 6

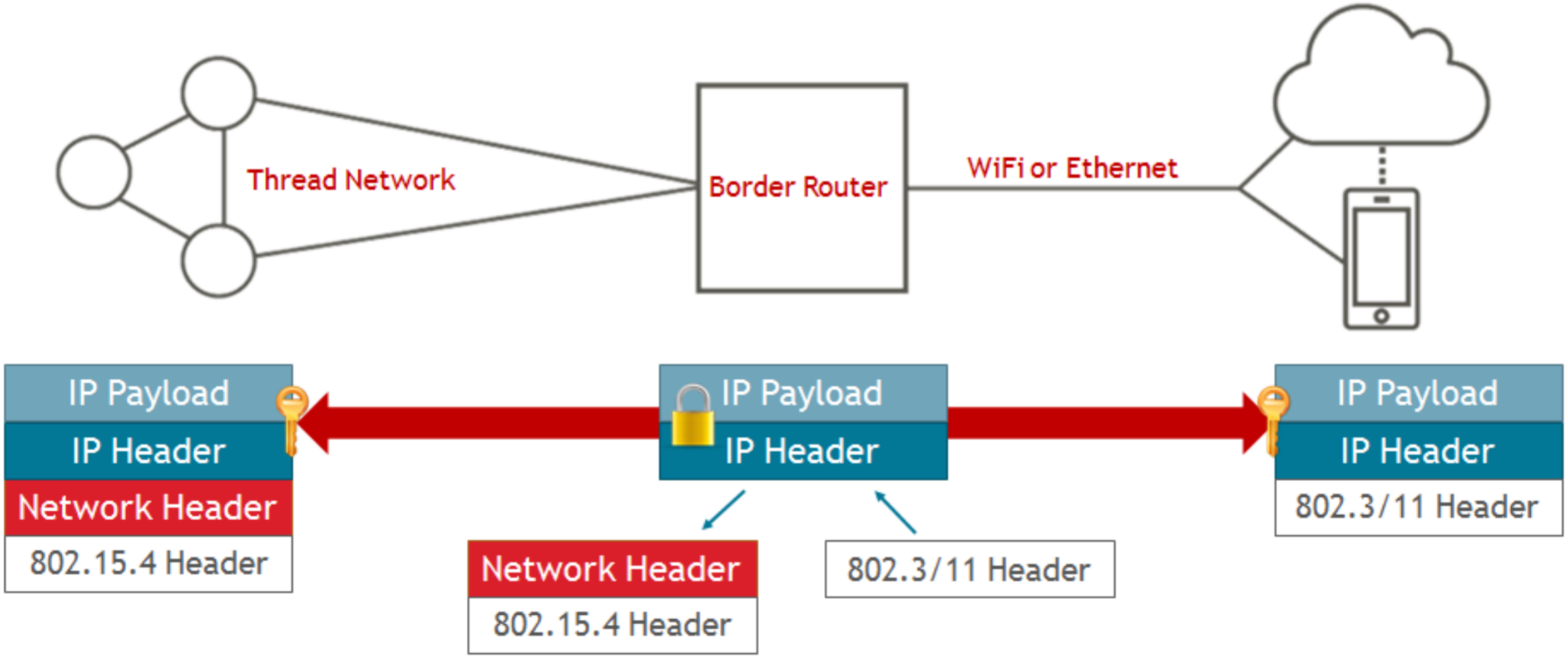


Mesh Network from AMX ZigBee white paper

Thread Networking key features

- IP-based:
    - Simplified bridging to other IP networks
- Flexible Network:
    - Simplified device types
- Robust:
    - No single point of failure
- Secure:
    - Simple security and commissioning
- Low Power Operation:
    - Support for sleeping devices

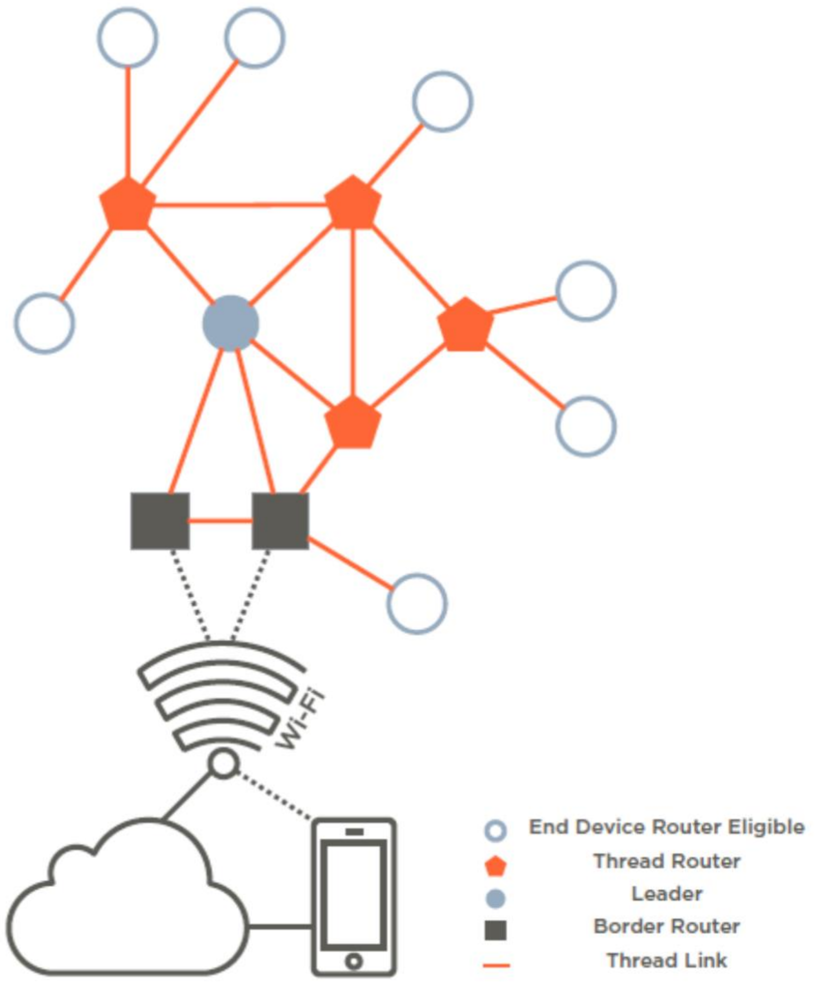
Thread - IP-Based: Simplified IP Bridging



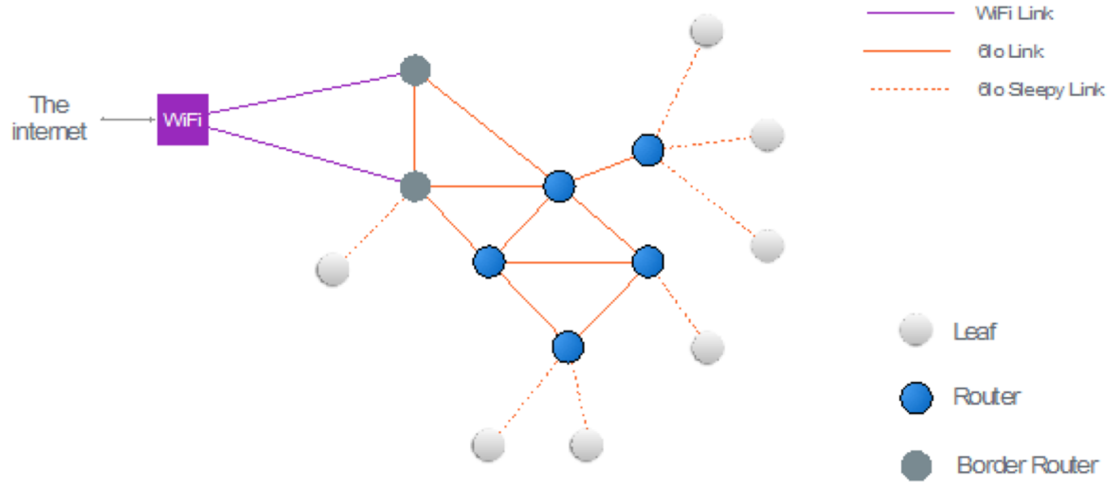
- Simplified bridging between mesh network and Internet
- Enables end-to-end IP security

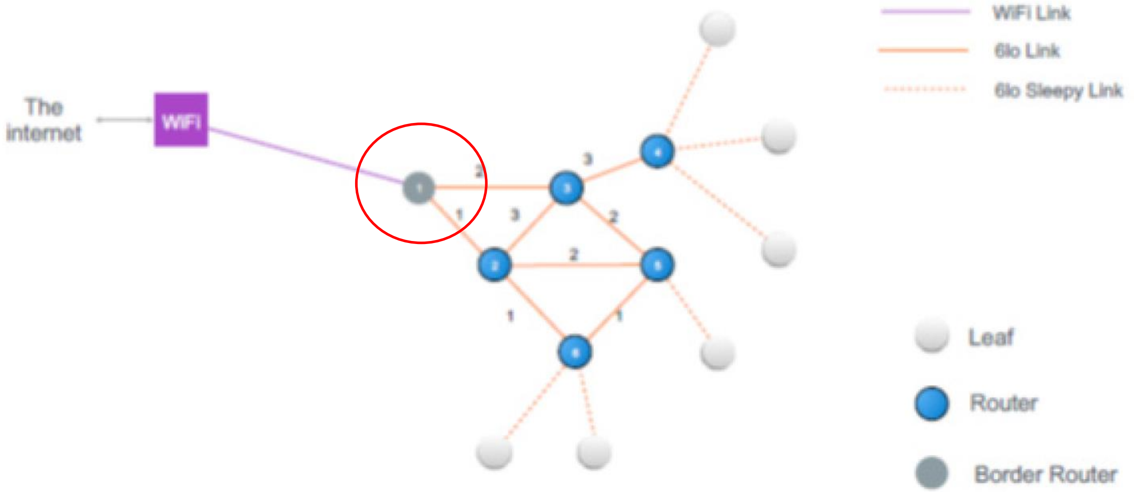
Thread - Flexible: Simplified Device Types

- Devices join as Router Eligible or End Device
- Router Eligible: Can become Routers if needed
  - First router on network becomes Leader
  - Leader: Makes decisions within network
- End Devices: Route through parent
  - Can be “sleepy” to reduce power consumption



No Single Point of Failure by Architecture



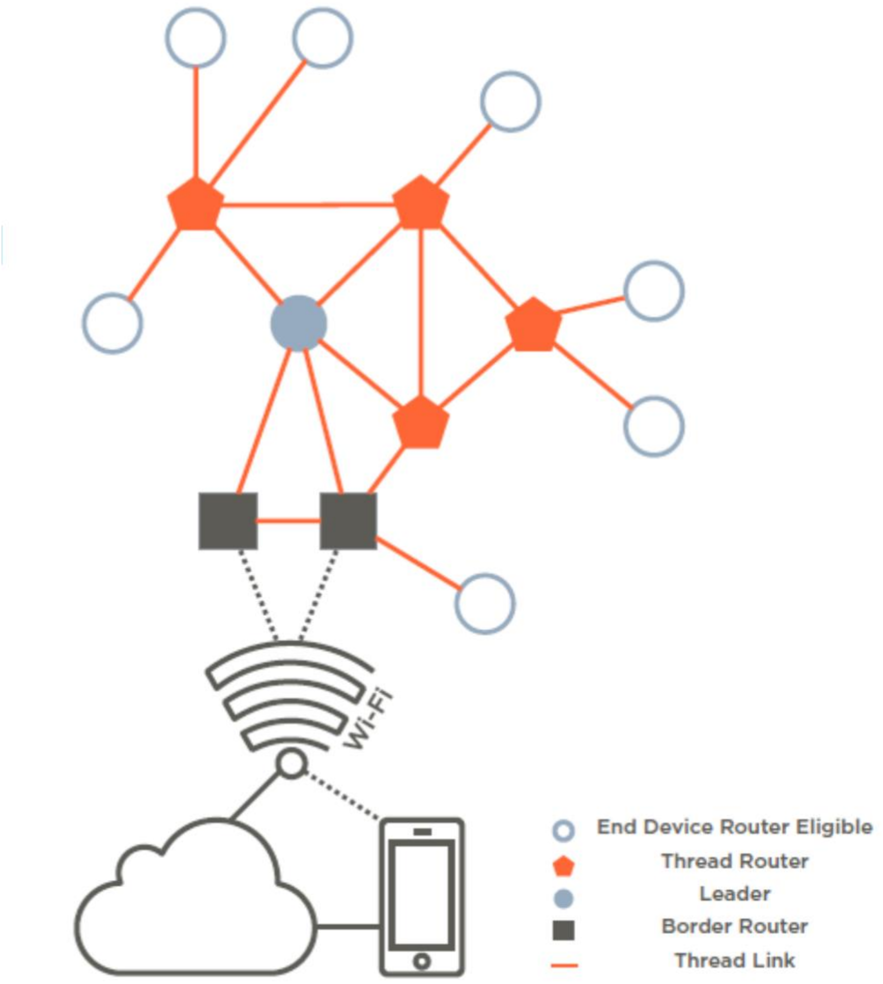


No Single Point of failure by architecture
And by design

Single Point of failure by design

Thread - Lower Power Operation: Sleepy Devices

- Sleeping devices poll parents for messages (or remote device if application configured)
- Sleeping device not required to check in to allow lower power operation
- Parents hold messages for sleeping devices
  - Parent will hold incoming data to a child for 90 seconds
- Sleeping device automatically switches parent if it loses connectivity



Thread Commissioning Model

- Devices must be securely authorized onto the Thread network by a user
- Can be done with a variety of devices
  - On network using a device with a GUI
  - On local Home network using border router
  - To the web using border router
- User must enter device passphrase which is used to authenticate device onto the network

Thread - Basic steps in Commissioning

- Two separate Authentications required:
  - Commissioning device authenticated as Active Commissioner – allowed to add devices to the network
  - Joining device is then authenticated by Active Commissioner – then device is provided network and security material to attach to the network
- Commissioning device is not provided network or security credentials due to security concern of having this material off network in devices

Thread – Commissioning (Authorizing the Commissioner)

- On network start up a commissioning passphrase is selected that is then used by commissioning devices to authenticate to the border router
  - User then has choice of providing this passphrase to other devices to allow them to commission
  - User can change this passphrase to eliminate other commissioning devices
- Commissioning device (off network) establishes a secure session (DTLS) with the border router using a commissioning passphrase (configured as initiation of border router and can be transferred between commissioning devices) using the commissioning passphrase
  - Border router request commissioning session from leader
- To ensure only one commissioner active at a time in the network
- Leader notifies network that a commissioner is active

Thread – Commissioning (Joining a device)

- Joining device looks for network that is actively commissioning and finds router on that network (Joiner router)
- Joiner router acts as security point and relays messages from joiner to commissioner
- Joining device and Commissioner establish DTLS session using devices short passphrase
- When device is authorized by commissioner, the joiner router is notified that it can provide network credentials to joining device
  - Commissioning does not have network and security material (to reduce security risk)
  - Credentials sent to joining device encrypted with key established during commissioning authorization and sent to joiner and joiner router
- Device can then attach to the network