Bluetooth

- Basic idea
  - Universal radio interface for ad-hoc wireless connectivity
  - Interconnecting computer and peripherals, handheld devices, PDAs, cell phones – replacement of IrDA
  - Embedded in other devices, very cheap
  - License-free ISM 2.45GHz
  - Relatively short range, low power, low data rate
  - Voice and data transmission

One of the first modules (Ericsson).

Bluetooth

- History
  - 1994: Ericsson (Mattison/Haartsen), “MC-link” project
  - Renaming of the project: Bluetooth according to Harald “Blåtand” Gormsen [son of Gorm], King of Denmark in the 10th century
  - 2001: first consumer products for mass market, spec. version 1.1 released
  - 2005: 5 million chips/week

- Special Interest Group
  - Original founding members: Ericsson, Intel, IBM, Nokia, Toshiba
  - Added promoters: 3Com, Agere (was: Lucent), Microsoft, Motorola
  - > 10000 members
  - Common specification and certification of products
Characteristics

- 2.4 GHz ISM band, 79 RF channels, 1 MHz carrier spacing
  - Channel 0: 2402 MHz ... channel 78: 2480 MHz
  - GFSK modulation, 1-100 mW transmit power
  - FHSS and TDD
  - Frequency hopping (spread spectrum) with 1600 hops/s
  - Hopping sequence in a pseudo-random fashion, determined by a master
  - Time division duplex for send/receive separation
  - Voice link — SCO (Synchronous Connection Oriented)
    - FEC (forward error correction), no retransmission, 64 kbit/s duplex, point-to-point, circuit switched
  - Data link — ACL (Asynchronous Connection Less)
    - Asynchronous, acknowledgments, point-to-multipoint, up to 433.9 kbit/s symmetric or 723.2/57.6 kbit/s asymmetric, packet switched
  - Topology
    - Overlapping piconets (stars) forming a scatternet

Piconet

- Collection of devices connected in an ad hoc fashion
- One unit acts as master and the others as slaves for the lifetime of the piconet
- Master determines hopping pattern, slaves have to synchronize
- Each piconet has a unique hopping pattern
- Participation in a piconet = synchronization to hopping sequence
- Each piconet has one master and up to 7 simultaneous slaves (> 200 could be parked)

Forming a Piconet

- All devices in a piconet hop together
  - Master gives slaves its clock and device ID
    - Hopping pattern: determined by device ID (48 bit, unique worldwide)
    - Phase in hopping pattern determined by clock
  - Addressing
    - Active Member Address (AMA, 3 bit)
    - Parked Member Address (PMA, 8 bit)
Scatternet
- Linking of multiple co-located piconets through the sharing of common master or slave devices
- Devices can be slave in one piconet and master of another
- Communication between piconets
- Devices jumping back and forth between the piconets

M=Master  
S=Slave  
P=Parked  
SB=Standby

Frequency Selection

Bluetooth Packets
- Packet structure
  - Access code
    - Channel, device access, e.g., derived from master
  - Packet header
    - active member address (broadcast + 7 slaves), link type, alternating bit ARQ/SEQ, checksum
SCO payload types

<table>
<thead>
<tr>
<th>Type</th>
<th>Payload (30)</th>
<th>Audio (10)</th>
<th>FEC (20)</th>
<th>Audio (10)</th>
<th>FEC (10)</th>
<th>Audio (10)</th>
<th>Header (1)</th>
<th>Payload (0-9)</th>
<th>2/3 FEC</th>
<th>CRC (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ACL Payload types

<table>
<thead>
<tr>
<th>Type</th>
<th>Payload (0-343)</th>
<th>Header (1/2)</th>
<th>Payload (0-339)</th>
<th>2/3 FEC</th>
<th>CRC (2)</th>
<th>Header (1)</th>
<th>Payload (0-17)</th>
<th>2/3 FEC</th>
<th>CRC (2)</th>
<th>Header (2)</th>
<th>Payload (0-121)</th>
<th>2/3 FEC</th>
<th>CRC (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DH1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DH2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DH3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DM4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DH4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data rates

<table>
<thead>
<tr>
<th>Type</th>
<th>Payload Header (byte)</th>
<th>User Payload (byte)</th>
<th>FEC</th>
<th>CRC</th>
<th>Symmetric max. Rate [kbit/s]</th>
<th>Asymmetric max. Rate [kbit/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACL</td>
<td>1 slot</td>
<td>1</td>
<td>0-17</td>
<td>2/3</td>
<td>yes</td>
<td>108.8</td>
</tr>
<tr>
<td></td>
<td>2 slot</td>
<td>1</td>
<td>0-27</td>
<td>no</td>
<td>yes</td>
<td>172.8</td>
</tr>
<tr>
<td></td>
<td>3 slot</td>
<td>2</td>
<td>0-121</td>
<td>2/3</td>
<td>yes</td>
<td>268.1</td>
</tr>
<tr>
<td></td>
<td>4 slot</td>
<td>2</td>
<td>0-218</td>
<td>no</td>
<td>yes</td>
<td>487.0</td>
</tr>
<tr>
<td></td>
<td>5 slot</td>
<td>2</td>
<td>0-224</td>
<td>2/3</td>
<td>yes</td>
<td>487.7</td>
</tr>
<tr>
<td>SCO</td>
<td>1 slot</td>
<td>1</td>
<td>0-29</td>
<td>no</td>
<td>no</td>
<td>185.6</td>
</tr>
<tr>
<td></td>
<td>2 slot</td>
<td>1</td>
<td>0-139</td>
<td>no</td>
<td>no</td>
<td>64.0</td>
</tr>
<tr>
<td></td>
<td>3 slot</td>
<td>1</td>
<td>0-20</td>
<td>2/3</td>
<td>no</td>
<td>64.0</td>
</tr>
<tr>
<td></td>
<td>4 slot</td>
<td>1</td>
<td>0-30</td>
<td>no</td>
<td>no</td>
<td>64.0</td>
</tr>
</tbody>
</table>

Data Medium: High rate, High-quality Voice, Data and Voice
Link Types

- Polling-based TDD packet transmission
  - 625µs slots, master polls slaves
- SCO (Synchronous Connection Oriented) – Voice
  - Periodic single slot packet assignment, 64 kbit/s full-duplex, point-to-point
- ACL (Asynchronous ConnectionLess) – Data
  - Variable packet size (1, 3, 5 slots), asymmetric bandwidth, point-to-multipoint

Robustness

- Slow frequency hopping with hopping patterns determined by a master
- Protection from interference on certain frequencies
- Separation from other piconets
- Retransmission
  - ACL only, very fast
- Forward Error Correction
  - SCO and ACL

Bluetooth Versions

- Bluetooth 1.1
  - also IEEE Standard 802.15.1-2002
  - initial stable commercial standard
- Bluetooth 1.2
  - also IEEE Standard 802.15.1-2005
  - eSCO (extended SCO): higher, variable bitrates, retransmission for SCO
  - AFH (adaptive frequency hopping) to avoid interference
- Bluetooth 2.0 + EDR (2004, no more IEEE)
  - EDR (enhanced data rate) of 3.0 Mbit/s for ACL and eSCO
  - lower power consumption due to shorter duty cycle
- Bluetooth 2.1 + EDR (2007)
  - better pairing support, e.g., using NFC
  - improved security
Bluetooth Versions

- Bluetooth 3.0 + HS (2009)
  - speeds up to 24Mbps (using co-located Wi-Fi link!)
- Bluetooth 4.0
  - Classic Bluetooth
  - Bluetooth High Speed
  - Bluetooth Low Energy
- Bluetooth Low Energy (BLE):
  - Marketed as Smart Bluetooth
  - Lower power, lower cost
  - Used in healthcare, fitness, security, entertainment devices
  - 40 channels
- Bluetooth Profiles (different types of applications)

Energy Consumption

- Traditional Bluetooth is connection oriented. When a device is connected, a link is maintained, even if there is no data flowing
- Sniff modes allow devices to sleep, reducing power consumption to give months of battery life (e.g., wake up every 100ms)
- Peak transmit current is typically around 25mA
- Even though it has been independently shown to be lower power than other radio standards, it is still not low enough for coin cells and energy harvesting applications

Bluetooth Low Energy (BLE)

- Bluetooth low energy is a new, open, short range radio technology
  - Blank sheet of paper design
  - Different to Bluetooth classic (BR/EDR)
  - Optimized for ultra low power
  - Enable coin cell battery use cases
    - < 20mA peak current
    - < 5uA average current
Short range wireless application areas

<table>
<thead>
<tr>
<th>Technology</th>
<th>Voice</th>
<th>Data</th>
<th>Audio</th>
<th>Video</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bluetooth ACL/HS</td>
<td>x</td>
<td>Y</td>
<td>Y</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Bluetooth SCO/SCO</td>
<td>Y</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Bluetooth low energy</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Y</td>
</tr>
<tr>
<td>Wi-Fi (VoIP)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Wi-Fi Direct</td>
<td>x</td>
<td>Y</td>
<td>Y</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>ZigBee</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Y</td>
</tr>
<tr>
<td>ANT</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>Y</td>
</tr>
</tbody>
</table>

*State = low bandwidth, low latency data*

BLE Basic Concepts

- Everything is optimized for lowest power consumption
  - Short packets reduce TX peak current
  - Short packets reduce RX time
  - Fewer RF channels to improve discovery and connection time
  - Simple state machine
  - Single protocol
  - ...

BLE Fact Sheet

- **Range:** ~150 meters open field
- **Output Power:** ~10 mW (10dBm)
- **Max Current:** ~15 mA
- **Latency:** 3 ms
- **Topology:** Star
- **Connections:** >2 billion
- **Modulation:** GFSK @ 2.4 GHz
- **Robustness:** Adaptive Frequency Hopping, 24 bit CRC
- **Security:** 128bit AES CCM
- **Sleep current:** ~1µA
- **Modes:** Broadcast, Connection, Event Data Models, Reads, Writes
BLE Fact Sheet

- **Data Throughput**
  - For Bluetooth low energy, data throughput is not a meaningful parameter. It does not support streaming.
  - It has a data rate of 1Mbps, but is not optimized for file transfer.
  - It is designed for sending small chunks of data (exposing state).

---

"Exposing State"

- It’s good at small, discrete data transfers.
- Data can be triggered by local events.
- Data can be read at any time by a client.
- Interface model is very simple (GATT).

---

BLE Architecture
BLE Device Modes

- **Dual Mode**
  - Bluetooth BR/EDR and LE
  - Used anywhere BR/EDR is used today
- **Single Mode**
  - Implements only Bluetooth low energy
  - Will be used in new devices / applications

BLE Physical Layer

- 2.4 GHz ISM band
- 1Mbps GFSK
- Larger modulation index than Bluetooth BR (which means better range)
- 40 Channels on 2 MHz spacing
BLE Physical Layer

• Two types of channels

BLE Physical Layer

• Advertising channels avoid 802.11

BLE Link Layer

• Link Layer state machine
BLE Link Layer

- Possible states:
  - Standby: not transmitting or receiving any data, and is not connected to any other device
  - Advertiser: periodically broadcasting advertisements
  - Scanner: actively looking for advertisers
  - Initiator: actively trying to initiate a connection with another device
  - Master: connected to another device as a master
  - Slave: connected to another device as a slave

BLE Advertising

- Devices can advertise for a variety of reasons:
  - To broadcast promiscuously
  - To transmit signed data to a previously bonded device
  - To advertise their presence to a device wanting to connect
  - To reconnect asynchronously due to a local event
BLE Advertising

- Four types of advertisements:
  - **Connectable undirected**: any scanner device can initiate a connection with this advertiser
  - **Connectable directed**: only one specific device can initiate a connection with this advertiser
  - **Non-connectable undirected**: no devices can initiate a connection with this advertiser; primarily used for general broadcast of data (up to 31 bytes of payload)
  - **Discoverable undirected**: any scanner device can request more information from the advertising device, but no devices can initiate a connection with it

BLE Data Transfer

- Once a connection is made:
  - Master informs slave of hopping sequence and when to wake up
  - All subsequent transactions are performed on the 37 data channels
  - Transactions can be encrypted
  - Both devices can go into deep sleep between transactions

Link Layer Connections

- Very low latency connection
Link Layer Connections

BLE Energy Characteristics

- From the previous slide, calculate energy per transaction
  - Assume an upper bound of 3ms per minimal transaction
  - Estimated TX power is 15mW (mostly TX power amp for 65nm chips)
    - For 1.5V battery, this is 10mA. 0.015W * 0.003 sec = 45 uJ
    - How long could a sensor last on a battery?
      - An example battery: Lenmar WC357, 1.55v, 180mAh, $2-5
      - 180mAh/10mA = 18Hr = 64,800 seconds = 21.6M transactions
      - Suppose this sensor sends a report every minute = 1440/day
      - For just the BT LE transactions, this is 15,000 days, or > 40 years
      - This far exceeds the life of the battery and/or the product
    - This means that battery will cost more than the electronics
      - This sensor could run on scavenged power, e.g. ambient light

BLE Use Cases

- Proximity
- Time
- Emergency
- Network availability
- Personal User Interface
- Simple remote control
- Browse over Bluetooth
- Temperature Sensor
- Humidity Sensor
- HVAC
- Generic I/O (automation)
- Battery status
- Heart rate monitor
- Physical activity monitor
- Blood glucose monitor
- Cycling sensors
- Pulse Oximeter
- Body thermometer
BLE Use Cases

- It can enable proximity detection
  - I’m in the car
  - I’m in the office
  - I’m in the meeting room
  - I’m in the movie theater
- It can enable presence detection
  - Turn the lights on when I walk around the house
  - Automatically locks the door when I leave home
  - Turn the alarm off if I’m already awake

BLE and Internet-of-Things

- My pulse is ...
- My blood glucose is ...
- My temperature is ...

BLE and GAP

- Generic Access Profile (GAP)
  - GAP defines a base profile which all Bluetooth devices implement, which ties all the various layers together to form the basic requirements for a Bluetooth device
  - GAP also defines generic procedures for connection-related services:
    - Device Discovery
    - Link Establishment
    - Link Management
    - Link Termination
    - Initiation of security features
BLE and GAP

- The GAP layer works in one of four profile roles:
  - Broadcaster: an advertiser that is non-connectable
  - Observer: scans for advertisements, but cannot initiate connections
  - Peripheral: an advertiser that is connectable and can operate as a slave in a single link layer connection
  - Central: scans for advertisements and initiates connections; operates as a master in a single or multiple link layer connections

BLE and GAP

- Non-discoverable Mode: No advertisements
- Limited Discoverable Mode: Device advertises for a limited amount of time before returning to the standby state
- General Discoverable Mode: Devices advertises continuously
- GAP manages the data that is sent out in advertisement and scan response packets
BLE and GAP - Pairing

- Pairing can be initiated by either the central or peripheral device
- The two devices generate and exchange short-term keys (STK) which can be used to decrypt data packets
- Either device can request to enable "bonding" to create a long-term relationship between the two devices
  - A long-term key (LTK) is generated, exchanged, and stored allowing device to re-encrypt the link quickly upon re-connection, without going through the complete pairing process once again
  - Profile / Service configuration data is remembered, so that the user does not need to re-configure the device every time they re-connect

BLE and GAP - Pairing

- Each device also states its input/output capabilities from among these options:
  - DisplayOnly – no way user can input anything into device, but it can output data
  - DisplayYesNo – user can input "yes" or "no" but nothing else; can also display data
  - KeyboardOnly – user can input a password or PIN, but no display
  - NoInputNoOutput – device has no means for user input, and has no display
  - KeyboardDisplay – device has a means for display as well as for input

BLE and GAP - Pairing

- Based on the combination of the capabilities of the two devices, one of two methods of pairing will be used:
  - Passkey entry – one device will display a randomly generated passkey, while the other will require the user to input the passkey. This allows for an authenticated link (MITM protection)
  - "Just Works" – the pairing process completes without requiring a passkey to be entered. The link will not be authenticated, but is encrypted
  - If either one of the two devices does not require authentication, then Just Works will be used by default, allowing the user to skip passkey entry
ZigBee

- IEEE 802.15.4 (similar to Bluetooth and IEEE 802.15.1)
- Pushed by Chipcon (now TI), Ember, Freescale (Motorola), Honeywell, Mitsubishi, Motorola, Philips, Samsung...
- More than 260 members
  - about 15 promoters, 133 participants, 111 adopters
  - must be member to commercially use ZigBee spec
- ZigBee platforms comprise
  - IEEE 802.15.4 for layers 1 and 2
  - ZigBee protocol stack up to the applications

ZigBee

- Design goal
  - Low power consumption
  - Simple Design
  - Few costs
- History
  - Zigbee-style networks began ~1998
  - IEEE 802.15.4 was first completed in 2003
  - ZigBee Alliance was established in 2002

ZigBee Core Market

- Industrial and Commercial
  - Monitors
  - Movement Sensors
  - Automation
- Personal Healthcare
  - Patient monitors
  - Remote Diagnosis
  - Data loggers
- Building Automation
  - Security
  - Lighting
  - Fire and Safety systems
- Automotive
  - Service controls
  - Inventory tracking
ZigBee Protocol Stack

- **Application Layer (AL)**
  - Application Framework (AF)
  - ZigBee Device Object (ZDO)
  - Application Support SubLayer (ASS)

- **Network (NWK)**
  - Star / Mesh / Cluster Tree

- **MAC**
  - Device Types / Channel Access

- **PHY**
  - 802.15.4 / 915 MHz / 2.4 GHz

---

**Device Type**

- **Full Function Device (FFD)**
  - Network router function
  - Any Topology

- **Reduced Function Device (RFD)**
  - Easy and cheap to implement
  - Limited to star topology

- **Personal Area Network (PAN) Coordinator**
  - Maintains overall network knowledge
  - Needs most memory and computing power

---

**Basic Topology**

- **Star Network**

- **RFD / EndPoint**
- **FFD / Router**
- **Coordinator**
Cluster Tree Network

ZigBee PRO: Mesh Network

Bluetooth vs. ZigBee

<table>
<thead>
<tr>
<th></th>
<th>Bluetooth (v1)</th>
<th>ZigBee</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol Stack</td>
<td>250 kb</td>
<td>&lt; 32 kb (4kb)</td>
</tr>
<tr>
<td>Range</td>
<td>10 - 100 meters</td>
<td>30 - 100 meters</td>
</tr>
<tr>
<td>Link Rate</td>
<td>1 Mbps</td>
<td>250 kbps</td>
</tr>
<tr>
<td>Battery</td>
<td>rechargeable</td>
<td>non-rechargeable</td>
</tr>
<tr>
<td>Devices</td>
<td>8</td>
<td>$2^{16}$</td>
</tr>
<tr>
<td>Air Interface</td>
<td>FHSS</td>
<td>DS/SS</td>
</tr>
<tr>
<td>Usage</td>
<td>frequently</td>
<td>infrequently</td>
</tr>
<tr>
<td>Network Join Time</td>
<td>long</td>
<td>short</td>
</tr>
<tr>
<td>Extendibility</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Security</td>
<td>PIN, 64 bit, 128 Bit</td>
<td>128 bit, AES</td>
</tr>
<tr>
<td>Feature</td>
<td>Option 1</td>
<td>Option 2</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>----------</td>
<td>----------</td>
</tr>
<tr>
<td>Brand</td>
<td>iPhone</td>
<td>Samsung</td>
</tr>
<tr>
<td>Model</td>
<td>7 Plus</td>
<td>S8</td>
</tr>
<tr>
<td>Display Size</td>
<td>5.5 in</td>
<td>5.8 in</td>
</tr>
<tr>
<td>Screen Resolution</td>
<td>1920 x 1080</td>
<td>1440 x 2960</td>
</tr>
<tr>
<td>Processor</td>
<td>A11</td>
<td>Snapdragon 835</td>
</tr>
<tr>
<td>RAM</td>
<td>2 GB</td>
<td>4 GB</td>
</tr>
<tr>
<td>Storage</td>
<td>32 GB</td>
<td>64 GB</td>
</tr>
<tr>
<td>Camera</td>
<td>12 MP</td>
<td>12 MP</td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>2900 mAh</td>
<td>3000 mAh</td>
</tr>
<tr>
<td>Battery Technology</td>
<td>Lithium-Ion</td>
<td>Lithium-Ion</td>
</tr>
<tr>
<td>Water Resistance</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Fingerprint Sensor</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Fingerprint Sensor Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
<tr>
<td>Iris Scanner</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Iris Scanner Location</td>
<td>Front</td>
<td>Front</td>
</tr>
<tr>
<td>Face ID</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Face ID Location</td>
<td>Front</td>
<td>Front</td>
</tr>
<tr>
<td>Facial Recognition Technology</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Facial Recognition Technology Location</td>
<td>Front</td>
<td>Front</td>
</tr>
<tr>
<td>Screen Protection</td>
<td>Screen Guard</td>
<td>Screen Guard</td>
</tr>
<tr>
<td>Screen Protection Location</td>
<td>Front</td>
<td>Front</td>
</tr>
<tr>
<td>Front Camera</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Front Camera Location</td>
<td>Front</td>
<td>Front</td>
</tr>
<tr>
<td>Rear Camera</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Rear Camera Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
<tr>
<td>Rear Camera Lens</td>
<td>f/1.8</td>
<td>f/1.7</td>
</tr>
<tr>
<td>Rear Camera Focal Length</td>
<td>21 mm</td>
<td>12 mm</td>
</tr>
<tr>
<td>Rear Camera OIS</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Rear Camera OIS Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
<tr>
<td>Rear Camera EIS</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Rear Camera EIS Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
<tr>
<td>Rear Camera Pixel Size</td>
<td>1.4 μm</td>
<td>1.4 μm</td>
</tr>
<tr>
<td>Rear Camera HelioSense</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Rear Camera HelioSense Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
<tr>
<td>Rear Camera HelioSense EIS</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Rear Camera HelioSense EIS Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
<tr>
<td>Rear Camera HelioSense Pixel Size</td>
<td>1.4 μm</td>
<td>1.4 μm</td>
</tr>
<tr>
<td>Rear Camera HelioSense Pixel Size Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
<tr>
<td>Rear Camera HelioSense Pixel Size EIS</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Rear Camera HelioSense Pixel Size EIS Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
<tr>
<td>Rear Camera HelioSense Pixel Size EIS EIS</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Rear Camera HelioSense Pixel Size EIS EIS Location</td>
<td>Rear</td>
<td>Rear</td>
</tr>
</tbody>
</table>