Recent Developments in Embedded System and IoT Protocols

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Abstract Embedded systems for Internet of Things (IoT) enable computation to be designed for a specific application, which is beneficial compared with general-purpose computing. In addition, embedded systems for IoT consist of embedded system and IoT communication protocols. Selection of the appropriate protocol for interprocessor communication (IPC) and IoT communication poses common challenges in the design of embedded systems. The evolution of data exchange and various wireless technologies has spurred numerous innovations for both protocols. This study discusses the common IPC methods and IoT communication protocols by comparing their features. The features include power consumption, security, spreading data rate, topology and applications. This analysis will guide researchers in selecting the right protocol when designing various applications.

Keywords: Embedded System, Internet of Things, Communication Protocol, Wireless Technology, Features

1. Introduction

Processes executed on one core, or several cores can interact with one another and coordinate their operations by using the interprocessor communication (IPC) control method. Algorithms are broken up typically into threads that execute on several cores. Data synchronization and exchange issues frequently arise across threads (Adiono et al., 2018). The IPC mechanism is used to accelerate the execution of an application with processes running on different cores. It enables data sharing between processors that are loosely coupled by using the multiprocessor interconnect facility and channel-to-channel communication links (Adiono et al., 2018). The shared memory model and the message forwarding model are the two basic IPC architectures. Real-time performance of parallel processing and parallel multithreading in multiprocessing systems rely heavily on IPC technology. The primary variables that affect interprocessor and interprocess interactions within certain architecture are the quantity of data, frequency of data transfer, speed of data transmission, latency, and the data transmission channel (Will et al., 2021; Millet et al., 2013). This condition clearly suggests that application performance becomes better with the increase in the number of processors running application processes simultaneously. When threads are implanted on a multiprocessor, numerical algorithms and applications with a high degree of parallelism, such as matrix multiplications, can be executed more quickly (Adiono et al., 2018; Jacobs & Bean, 1963; Mueller, 2010). For the reader to know when the writer has finished and the writer to know when the reader is ready for more data, two concurrent operations that are writing and reading data must synchronize in some way. Recent approvals of the Advanced Microcontroller Bus Architecture and Advanced eXtensible Interface protocols enable many processors in embedded systems to share resources, including Inter-integrated Circuit (I^{2}C), Universal Asynchronous Receiver/Transmitter (UART), and Serial Peripheral Interface (SPI) in addition to IPC serially across microcontrollers (Uemura & Suda, 2010; Miller & Freeman, 2019). Any of the numerous additional UNIX interprocess communication techniques, such as sockets, shared memory, and messages (Hossain &Tokhi, 2002; Dahnoun & Multicore, 2018), can be used by multiple processes. The Internet of Things (IoT) is predicted to revolutionize the way information is shared between people, objects, and other things. Connected, information-transferring, and decision-making capabilities exist in smart gadgets. It is a new innovative technology known as “connectivity for anything”. Anywhere, anytime, and everything can be connected. Although many smart devices are available in the IoT world, they are subjected to several limitations, such as processing power, storage space, power lifespan, and radio range. Therefore, the IoT deployment needs communication protocols that can effectively handle these circumstances (Tan and Wang, 2010). This review article aims to provide a detailed comparison in terms of the pros and cons, power, speed, and power consumption between three IPC technologies and seven IoT communication protocols.

2. Types of Communication Protocols

2.1 Inter-Processor Communication Protocol

The main benefit of embedded systems is that only an extremely small number of pins are required to enable serial communication at very respectable rates. This condition is crucial because microcontroller units and system on chips only have a finite number of pins available. Serial communication interfaces are utilized by an extremely large number of sensors and peripheral modules. No clock is used in asynchronous serial communication, whereas a clock line is used in synchronous serial communication to synchronize data transmission, and sampling is performed regarding clock pulses in the two cases. One-way data transfer occurs during simplex, half-duplex, and full-duplex communication, whereas two-way data transfer occurs during the latter two. The I^{2}C, UART, and SPI approaches are described in depth below, along with comparison

2.1.1 I^{2}C

I^{2}C was created by Philips Semiconductor. It has several master and slave devices. I^{2}C is frequently referred to as a two-wire interface because a complete communication bus can be established with only two wires.

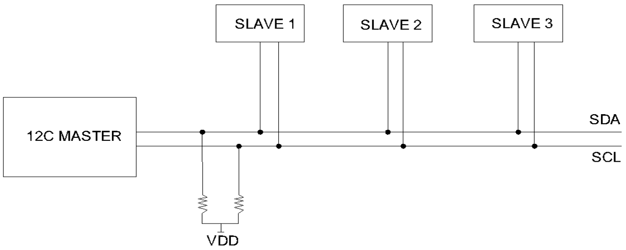


Figure 1. I^{2}C communication

I^{2}C is a half-duplex synchronous communication protocol, which indicates that two sharing devices must use the same clock signal, as shown in Figure 1 (Texas Instruments, 2018). A clock line is used in synchronous serial communication to synchronize data transfer, and sampling occurs in relation to clock pulses. Only two wires are available for information sharing, where the first one is used to transmit the serial clock (SCL), and the other is utilized to send and receive serial data (SDA). I^{2}C has the advantage of only requiring two lines per bus; one for the clock and one for the data for all connected devices. I^{2}C is slower in terms of speed compared with other communication techniques. This condition is because only one processor transmits at a time during half-duplex data transfer or transmission and reception does not occur concurrently (Leens, 2009). With pull-up resistors indicated as R1 and R2 in Figure 1, the I^{2}C protocol only has SCL and SDA.

2.1.2 UART

A device circuitry called a UART is used to create serial communication between two CPUs or other serial peripherals and modules. UART is a two-wire bus compared with I^{2}C that does not employ addresses to identify the devices attached to it. Thus, only two UART devices may be connected to each bus at a time to interact with one another, as shown in Figure 2. Data are converted into packets for UART to deliver and reconstruct them from packets it receives. Incoming parallel data are converted to serial data by the device, which then transmits the data via the communication connection (Nanda and Pattnaik, 2016).

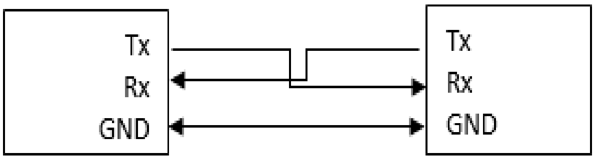


Figure 2. UART communication

The UART Tx processor turns data bytes into bits before delivering them. Bits must be split to create packets to be transferred. A start bit, a data frame, a parity bit, and stop bits are included in each packet. Figure 3 shows a simple structural example of a data packet that is prepared for transmission (Ferrari & Ferrari, 2002).

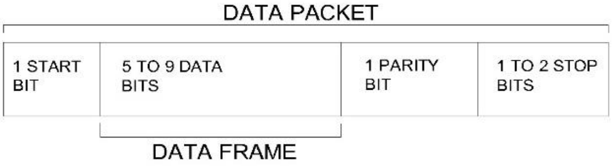


Figure 3. Example of Data Packet

On the other side, the receiving device detects the mistakes by computationally comparing the received bits through its receive pin, Rx. If no are mistakes found, then the received bits will be stripped to produce the data frame, which includes the delivered message. Bit receiving continues until the transmission is completed, at which point the whole byte is rebuilt from data frames for use by subsequent receiver operations. The received byte is kept in the UART buffer by a UART receiver processor. A data loss during transmission may be determined by using the parity bit. A bit's status changing while it is being transferred results in data loss (Gasperi & Hurbain, 2009). The typical obstacles that cause a data bit to change states include transmission distances, magnetic radiations, and incompatible baud rates (e.g., 0–1 or 1–0). The UART technique's settings on the two processors must be the same to create appropriate communication between them. For proper error detection and correction, the following settings are required: same baud rate, same data length, same parity bit, and same number of stop bits.

2.1.3 SPI

Motorola created the full-duplex serial synchronous communication protocol known as SPI to swiftly establish communication across short distances between two microcontrollers or a microcontroller and one or more peripheral devices (Leens, 2009; Stan, 1983). SPI allows for the establishment of full-duplex serial communications without addressing serving as the manner of device selection (Leens, 2009). Only one master is allowed per system using the SPI approach; additional devices may only act as slaves by connecting to various slave select lines. This protocol specifies the use of four signal lines: Serial Clock (SCK), Slave Select (SS), Master in Slave Out (MISO), and Master Out Slave In (MOSI), as shown in Figure 4 (Leens, 2009; Stan, 1983; Moskowitz, 2016). MISO is the slave line for sending data to the master. MOSI is the master line for sending data to the peripherals. SCK is the clock pulse that synchronizes data transmission generated by the master. SS pin is allocated on each device which the master can use to enable and disable specific devices and avoid false transmissions due to line noise. The slave line attached to the slave device must be set low for a master to communicate. SPI is often used as a bus with one master and many slaves, where each slave requires a slave select line.

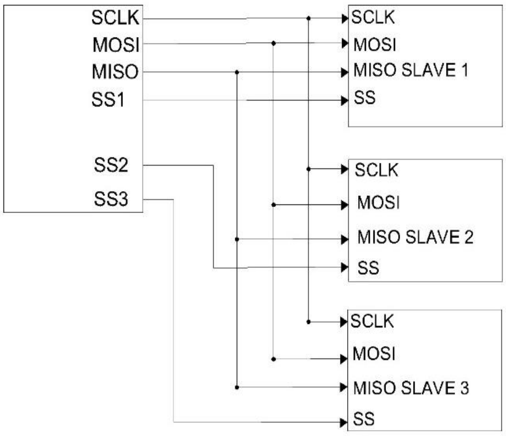


Figure 4. SPI communication

The master must set the clock to a frequency that the slave device wants to interact to function as an SPI master. The slave device is toggled when the clock has been set up and the SS line is low. On the SCK line, the master generates the clock, and one bit is sent from the master to the slave and vice versa during each clock cycle. Each device cannot receive data without transmitting them, and vice versa; hence, communication is always full duplex (Shahmiri et al., 2020). The hardware is configured typically so that the master and the slave have an 8-bit shift register. The shift register in the slave is linked to the MOSI, and MISO is connected to the shift register in the master. The registers need to change values at eight clock cycles, concluding a full duplex byte transmission and receiving. The simultaneous shifting of data into and out of the master and slave registers is depicted in Figure 5.

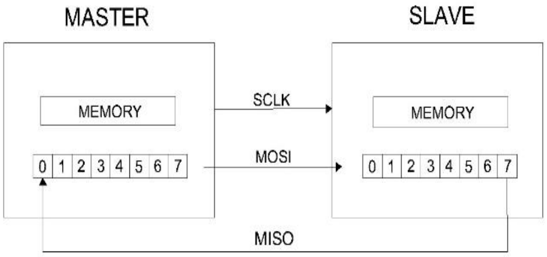


Figure 5. SPI Shift Register Bit Transfer

The slave should have data preloaded in its register so that it may send them concurrently when the master commences communication with the slave (Depari et al., 2020). The master will transmit a command and wait the required number of clock cycles before sending the slave's answer to accommodate this process. Dummy bytes can be used to accelerate transfers in cases where only half-duplex communication is required because read-only and write-only operations are not supported (Fruitwala, 2021). For instance, if a master needs data from a slave but has nothing to deliver, then it will load a fake byte into its register. Each slave on a SPI bus connected to several slaves in a typical arrangement includes a SS line. Pull-up resistors are advised to be placed between the SS lines and the device when implementing SPI without a module on board to lessen crosstalk (Huang & Wang, 2020; Shirriff, 2016).

2.2 IoT Communication Protocol

Connectivity is one of the foundational elements of IoT. It is made up of a vast network of components, including both physical and immaterial things of various sizes and shapes that are linked together to exchange information. The data is acquired and used to automate processes or support decision making. Different communication and network protocols are required because of the wide range of data kinds and applications. IoT communication protocols may often be divided into two groups: Low Power Wide Area Network (LPWAN) and Short-Range Network.

2.2.1 LPWAN

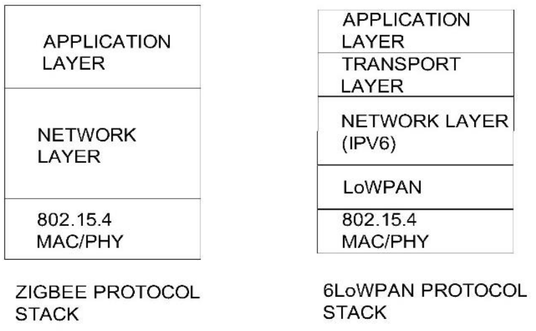
LPWAN is a wireless wide area network technology that interconnects low-bandwidth, battery-powered devices with low bit rates over long ranges. Created for machine-to machine (M2M) and IoT networks, LPWANs operate at a lower cost with greater power efficiency than traditional mobile networks. They can also support a greater number of connected devices over a larger area. Sigfox and cellular are the examples of LPWAN technology.

A low power technique called SigFox is used to wirelessly communicate with a wide variety of low energy items, including sensors and M2M applications. It permits the transfer of modest volumes of data over distances of up to 50 km. Ultra-narrow band technology is used by SigFox. This technology is powered by a small battery and only intended to handle slow data transfer rates of 10 bits to 1000 bits per second. Smart meters, patient monitoring, agricultural equipment, security gadgets, streetlights, and environmental sensors all utilize near-field communication technology. Star network topology is supported by SigFox (Tan & Wang, 2010; Li et al., 2011).

Cellular technology is suitable for IoT applications that demand operation over greater distances and have a power source that requires high throughput data. It may utilize the GSM/3G/LTE/4G/5G cellular connection capabilities to offer dependable high-speed internet connectivity, but it consumes high power. Thus, M2M or local network connectivity is inappropriate. Numerous applications, particularly those involving mobile devices, employ the cellular communication protocol. Technology-based factors influence cellular topology (Tan & Wang, 2010; Porkodi & Bhuyaneswari, 2014; Samie et al., 2016). LTE system is intended to be a packet-based system with fewer network components, which increases system capacity and coverage, and offers high performance in terms of high data rates, low access latency, flexible bandwidth operation, and seamless integration with other existing wireless communication systems. EPC and E-UTRAN are the two components that make up the LTE network. In comparison to 3G wireless networks, LTE/LTE-A networks provide various additional features and entities. The 3GPP committee recommends a brand-new base station type called HeNB to increase network capacity and interior coverage (Cao et al., 2013). 5G, the next generation of wireless communications, differs from current 4G LTE networks because it offers extremely high data rates (typically of the order of Gbps), extremely low latency, a massive increase in base station capacity, and remarkable improvement in users' perceived quality of service (Agiwal et al., 2016).

2.2.2 Short Range Network

Short range network refers to the technology that can communicate wirelessly within a smaller diameter region, within a minimum level of 1 mm. The common short-region wireless communication modes are Wi-Fi, Zonal Intercommunication Global-standard (ZigBee), and Bluetooth. Some technologies, such as infrared ray, visible light communication, Internet of cars, and Internet of bodies, are not widely used and approved. Some of the instances of short-range network are discussed below. For IP-based standard internetworking protocol, 6loWPAN is the first and most popular standard in IoT communication protocols. Without the use of intermediary structures, such as translation gateways or proxies, connecting straight to another IP network is possible. The Internet Engineering Task Force has developed this standard for Internet Protocol (IP) communication over IEEE802.15.4 low-power wireless networks using Ipv6 (Aragues et al., 2012; López et al., 2013). The number of addresses is more than sufficient because it allows 128-bit IP addresses. This feature aims to accommodate addresses of different lengths. This protocol has a reasonable price and consumes low power. Different topologies, including mesh and star topologies, are supported by 6LoWPAN (Rathnayaka et al., 2011). To address compatibility between IEEE 802.15.4 and IPv6, 6LoWPAN suggests adding an adaption layer between the media access control (MAC) layer and the network layer IPv6. ZigBee is the most competitive substitute for 6LoWPAN, as shown in Figure 6. At the physical layer, 6LoWPAN and Zigbee employ the same IEEE 802.15.4 protocol (Al-Sarawi et al., 2017; Le et al., 2012).



ZIGBEE PROTOCOL STACK

6LoWPAN PROTOCOL STACK

Figure 6. Zigbee and 6LoWPAN Protocol Stack

The ZigBee protocol was developed by the ZigBee Alliance based on the IEEE 802.15.4 standard for low-power wireless networks. ZigBee is a standard that was developed to operate with high-quality, low-cost communication protocols, compact, and low-power digital radios that can send data farther for personal area networks. It is also utilized in applications that call for low data rates, extended battery life, and secure networking hardware. ZigBee may support a variety of network topologies, including mesh, star, and tree topologies (Tan & Wang, 2010; Al-Sarawi et al., 2017).

A crucial protocol for IoT applications is BLE, commonly referred to as Bluetooth smart. It is created and improved for IoT applications that require short-range, low bandwidth, and low latency communication (Hughes et al., 2015; Sanchez-Iborra & Cano, 2016; Cerruela García et al., 2016). Less setup time, less power consumption, and support for star network topologies with an infinite number of nodes are some benefits of BLE compared with traditional Bluetooth (Tan & Wang, 2010; Al-Sarawi et al., 2017).

The DASH7 Alliance, ISO, IEC, ASTM International, and EPC-global are only a few of the standards for RFID. RFID systems comprise an RF tag, a tiny radio frequency transponder, and a reading device called a reader. This tag is electronically encoded with special data that can be read from a distance (Le et al., 2012). Two RFID tag system technologies are available: the first is known as an active reader tag system, and the second is known as a passive reader tag system. Passive tags operate on lower frequencies and lack an internal power source, and active tags are battery-powered, costlier, and use higher frequencies. RFID information cannot be utilized directly for measurement or diagnostic data because it is static and must be encoded into the tag. Smart retail, healthcare, national security, and agriculture are a few IoT applications that use RFID. RFID is compatible with peer-topeer network structure (Hughes et al., 2015; Goursaud & Gorce, 2015; Gomez & Paradells, 2010; Alarcon-Aquino et al., 2008).

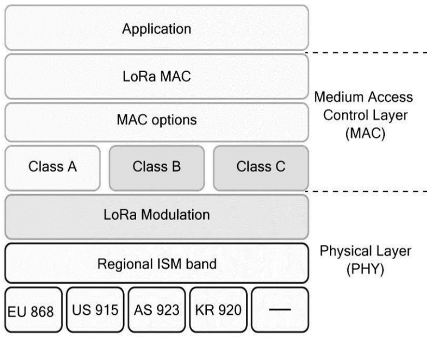


Figure 7. LoRa Protocol Stack

LoRa is a long-range, low-power wireless technology with the goal of extending battery life, supporting many connected devices, and enhancing network capacity and robustness (Azamuddin & Raj, 2015; LoRa, 2015). LoRa technology has two layers: physical and MAC, as shown in Figure 7. The physical layer is based on chirp spread spectrum, which provides high sensitivity for the receiver. The resilience against noise is strengthened because of the forward error correction messages employed in this layer (Noreen et al., 2017). The LoRa Alliance has standardized the MAC layer protocol and system architectural design known as LoRaWAN (Saban et al., 2021). LoRa technology utilizes unlicensed wireless bandwidth in the industrial, scientific, and medical band (ISM).

3. Comparison of Communication Protocols

This section aims to provide a guideline for researchers to select the right communication protocol by providing a comparison between the above-mentioned communication protocols for IPC and IoT protocol. Different criteria are used to benchmark the differences between the communication protocols.

3.1 IPC Protocol

SPI is better suited for applications in which devices deliver data streams, but I²C is better at multi-master "register access" applications. I²C, UART, and SPI all provide decent support for communication with low-speed devices in terms of speed. Additionally, UART, the slowest protocol, only allows for master-slave communication between two devices. SPI consumes the most power, followed by UART and I²C, in that order, respectively.

I²C and SPI both allow for a maximum of two slaves to be linked to the master, giving you the option to further extend other peripherals like LCDs, GSMs, and GPSs. UART can only have one slave attached to a master at once, which restricts the extension of the peripherals.

UART is frequently used in microcontrollers for a range of peripheral modules, including Bluetooth, GPS, and other sensors. Additionally, SPI is used in sensors, control devices, communications, and memory access technologies including flash, EEPROM, and SD cards. It works incredibly well for short-range communications, enabling high-performance microcontroller interfaces with nearby peripherals (Al-Sarawi et al., 2017; Le et al., 2012). On the other hand, I²C has a wide range of uses and is preferred by EEPROMs, ADCs, LCD displays, real-time clocks, and sensors.

Table 1 represents the comparison among I²C, UART, and SPI in terms of speed, synchronization, transmission mode, number of master and slave, pin connection, and power consumption. The advantages and disadvantages of these communication protocols are compared.

3.2 IoT Communication Protocol

All seven communication protocols contain procedures for authentication and encryption in terms of security. Cellular and RFID employ RC4, 6LoWPAN, ZigBee, and BLE, an Advanced Encryption Standard (AES) block cypher with counter mode. However, several remarkable flaws were found. RC4 and AES lack security, but RC4 is much faster than AES.

6LoWPAN, ZigBee, and BLE are low-power wireless technologies intended for mobile devices with finite battery capacities. They have minimal power usage. The data rates of 6LoWPAN, ZigBee, BLE, and SigFox are all equal to 1 Mbps. However, RFID has the highest data rate of 4 Mbps. SigFox and Cellular have a range that is more than the coverage of a few kilometers. However, the range of 6LoWPAN, ZigBee, BLE, and RFID is limited and only covers a few kilometers. A comparison of the IoT communication protocols shown in Table 1 indicates that 6LoWPAN, which is an IP-based, will be the protocol of the future. The vast IPv6 address spaces are utilized for data and information gathering through the features and behavior of various metrics. The metrics are low bandwidth, different topologies, power consumption, low cost, and scalable networks. IPv6 enables a huge number of smart devices to be deployed over the Internet easily.

Table 1. Comparison among I²C, UART and SPI

Feature	I²C	UART	SPI
Throughput (kHz)	100, 400, 1000, 3400, 5000	9.6, 19.2, 115.2	No limit
Protocol complexity	Low	Low	Lower
Delivery delay	Vary depending on the speed of the I2C bus, the length of the wires used for the communication, and the number of devices connected to the bus.	Vary depending on the baud rate of the communication, the size of the data packets being transmitted, and the presence of any flow control mechanisms.	Vary depending on the clock speed of the SPI bus, the length of the wires used for the communication, and the number of devices connected to the bus.
Energy consumption	Vary depending on the speed of the I2C bus, the voltage levels used for the communication, and the number of devices connected to the bus but in general it is low power consumption	Vary depending on the baud rate of the communication, the voltage levels used for the communication, and the number of devices connected to the bus but generally it is low power consumption	Vary depending on the clock speed of the SPI bus, the voltage levels used for the communication, and the number of devices connected to the bus but in general it is relatively high-power consumption
Transmission mode	Half-duplex	Full-duplex	Full-duplex
Number of possible masters	More than 1	1	1
Number of possible slaves	More than 1	1	More than 1
Pin connections	2	2	4
Power consumption	Moderate	Low	High

Security method	Digital certificates or encryption keys. Use a secure bootloader	Authentication, encryption of transmitted data, and the use of secure bootloaders.	Data encryption and device authentication. Less secure and may not be the best choice for transmitting sensitive information.
Application	Better for multiple pheripheral	Use for range application e.g Bluetooth and GPS	Better for dilivering data stream

Table 2. Comparison among IoT Communication Protocol

Characteristic	SigFox	Cellular	6LoWPan	ZigBee	BLE	RFID	LoRa
Standard	SigFox	3GPP and GSMA, GSM/GPRS/EDGE (2G), UMTS/HSPA (3G), LTE (4G), 5G	IEEE 802.15.4	IEEE 802.15.4	EEE 802.15.1	RFID	IEEE 802.15
Frequency band	68 MHz (EU) 902 MHz (USA)	Common Cellular bands	M2M 868 MHz (EU) 915 Mhz (USA) 2.4 Ghz (Global)	2.4 GHz	2.4 GHz	25 kHz, 13.56 MHz, 902-928 MHz	125 kHz, 250 kHz or 500 kHz
Network	LPWAN	WPAN	WPAN	WPAN	WPAN	Proximity	LPWAN
Topology	Star Network	N/A	Star Mesh Network	Star, Mesh Cluster Network	Star –Bus Network	P2P Network	Star Network
Power	10 mW - 100 mW	High power consumption	1-2 years lifetime on batteries Low power	30 mA Low power	30 mA Low Power	Ultra-low power	1.8V to 3.7V
Data rate	100 bps (UL), 600 bps (DL)	N/A	250 kbps	250 kbps	1 Mbps	4 Mbps	50 kbps.
Range	Long Range 10km (URBAN) 50km (RURAL)	Several km	Short Range 10-100m	Short Range 10-100m	Short Range ~15-30 m	Short Range Up to 200 m	Few to 10 km
Security	Partially addressed	RC4	AES	AES	E0 Stream AES-128	RC4	NA
Applications	Street Lighting Energy meters	M2M	Monitor and Control via Internet	Home industry monitoring and controlling	Wireless headsets, Audio Applications	Tracking, Inventory, Access	Smart city applications

4. Conclusion

Although many protocols are used for IPC and IoT, each of them has certain specifications and benefits. The system architect is responsible to decide which one is perfect in designing an embedded system for IoT. Therefore, the question that someone needs to answer is “which technology is the best one for my application”. This study reviews and compares the common IPC and IoT based on different criteria used. Speed and power consumption are vital parameters for IPC and IoT protocols. Other important criteria determine the number of slaves and masters for IPC protocols. For the IoT protocol, the important criteria are network, topology, range, cryptography, and power consumption. With all these criteria, the challenges to decide which protocol to be used when designing an embedded system for IoT can be addressed. These parameters serve as reference for researchers or designers to perform decision making and application.

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