Chapter 3
Advanced Communications in Cyber-Physical Systems

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3.1 Introduction

The recent technological developments offer us a new generation of systems known as cyber-physical systems (CPSs). The emergence of CPSs introduces specialized networking and communication strategy, information technology, integrating them with physical world which enables the advancement of a new vision for the social facilities. A CPS is the integration of computation, communication, control, learning, and reasoning with physical processes. CPSs cannot be considered as conventional real-time systems or embedded systems. There are several features that exist in CPSs which make it different from other systems such as dynamically reconfigurable, fully automation, auto-assembly, and integration. A definition of CPSs was provided by Shankar Sastry from University of California, Berkeley in 2008 [1]:

> A cyber-physical system (CPS) integrates computing, communication and storage capabilities with monitoring and/or control of entities in the physical world, and must do so dependably, safety, securely, efficiently and real-time.

Cyber-physical systems provide a number of advantages. CPSs are safe and efficient engineered systems that control and integrate entities forming sophisticated systems with new competences and capabilities. CPSs can be applied extensively in several domains offering ample chances such as infrastructure control, energy control, environmental control, efficient transport system, tele-medicine, medical devices, assisted living, and agriculture. Complex systems having critical infrastruc-

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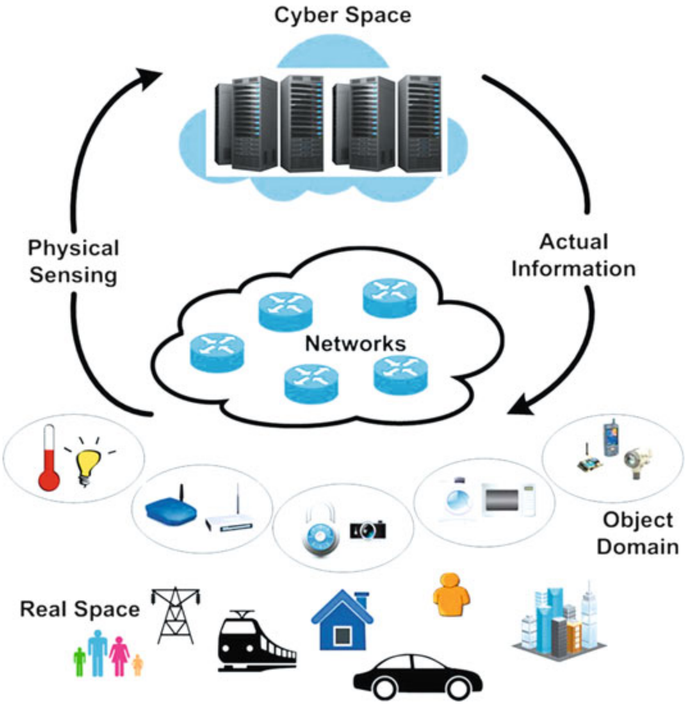


Fig. 3.1 Interconnection between cyber and physical objects [2]

ture such as water supply, gas production, electricity generation and distribution, and oil production are also outcome of CPSs.

The applications of CPSs expand from small systems (i.e., aircrafts) to very large systems (i.e., power grid). The interaction between cyber and physical object is shown in Fig. 3.1. Distinguished features of CPSs make it different from conventional wireless sensor network (WSN), desktop computing, and embedded systems. For example, the health care systems contain health information network, patient record, home care, operation management, hospitals and operating rooms, surgery and therapy, etc. Most of these tasks related to health care are highly controlled by computer systems with hardware and software components. Medical devices and systems need to be fully communicated and to act according to the patients' needs. Hence, medical devices are required to be dynamically reconfigured based on the circumstances of patients. For instance, devices such as infusion pumps, automatic oxygen delivery systems and sensors observing patient conditions need to be integrated into a new robust system to fulfil the patient needs. The main challenges in designing such CPS are maintaining safety, security, and reliability. Power management is another application of CPS which includes power electronics, power grid, and embedded control software integrated forming an efficient solution.

These types of CPS need specialization to ensure fault tolerance, security, safety, and decentralized control.

The research related to CPSs is still in embryonic stage. Currently, most of the research works are focused on specific domains such as networking, sensors, mathematics, computer science, system theory, and software engineering. For instance, complex systems are modeled utilizing diverse modeling methods, formalisms, and tools. A specific method or formalism is well suited to characterize either the cyber or the physical process but not both. CPSs are anticipated to be engineered systems that are versatile having robustness, self-organization, self-maintenance, autonomy, self-repair, efficiency, predictability, interoperability, global tracking and tracing, etc. There exist several challenges pertinent to CPSs that have to be addressed. The distinguished features of CPSs which make design of CPSs a challenging research issue are summarized below.

- Integration: CPSs integrate computation, control, and communication with physical world. Furthermore, some CPSs may have to integrate with other systems or other CPS [3]. For example, integration of CPS and cloud which may perform many tasks such as controlling power, storage, and data services [3].
- Limited capability: Some CPSs utilize devices with very limited capabilities and functionalities. Reason behind this is that the currently available devices may have limited capabilities. Besides, cost limitation is another reason. Such devices generally have limited computing, processing, communication, and storage capabilities.
- Heterogeneous devices: CPSs are conformed to several heterogeneous devices such as sensors, actuators, controllers, microcontrollers, networking devices, and communication devices. Moreover, these devices may operate at different location in different physical environments.
- Networks of different scales: CPSs include different types of networks such as wired/wireless network, Bluetooth, WLAN, mobile ad hoc network (MANET), and GSM in a distributive fashion. Besides, the scales of these networks and the types of devices are widely diversified.
- Power limitations: Some devices of CPS may be deployed in remote locations where no stable power sources are accessible. Therefore, the communication protocols of CPSs should be modeled considering the power limitations.
- Distributed control: Some CPS applications necessitate distributed control, processing, and decision making [3] to operate successfully. Furthermore, many applications require parallel processing for quick and prompt decision making.
- Real-time operations: CPSs often require to operate and take decision in real-time. Besides, real-time operations also include real-time sensing, processing, communication, and response.
- Special communication: Some CPSs need specialized communication among different subsystems and the devices. Thus, communication among devices should be reliable and robust. More emphasis should be given in designing optimized communication techniques.

- Complexity regarding temporal and spatial scales: Most of CPSs may have to control multiple components at different time in different locations which make the networking paradigm of CPSs more complex.
- Dynamic adaptation: To cope up with different unpredictable environments, CPSs may have to reconfigure system settings. Hence, CPSs should have adaptive capabilities.
- Synchronization of control loops: CPSs are the outcome of collaboration man–machine where the information is circulated as loop from man to machine and machine to man. Therefore, CPSs should be integrated with advanced and synchronized feedback control technologies.
- Mobility: CPSs often include mobile devices which need proper synchronization to be connected with the rest of system. As mobile devices change locations frequently, specialized communication mechanism is needed to handle mobility in CPSs.
- Fault tolerance and reliability: CPSs applications are generally large-scale complicated embedded systems; hence, different types of fault should be detected and dealt with efficiently without hampering any regular operations of CPSs.
- Security and privacy: Most of CPSs involve distributed applications. Thus, the security and privacy of the information must be preserved.
- Context awareness: CPSs sometimes need to know the context of whole systems such as system status, locations of physical object to operate properly. Hence, proper synchronization and exchange of information are required for successful operation.
- Verification, validation, and certification: The relation between used methods and testing requires to be validated. The heterogeneous nature of CPS models needs compositional verification and testing methods.

Generally, a CPS integrates sensors, actuators, and controller with physical objects in large-scale. The operation of CPSs is usually divided among several subsystems. CPSs are considered as a form of wireless sensor and actuator networks (WSANs) [4, 5]. Here, sensors sense information about the physical world and actuators along with controllers process this information to take appropriate decisions. The performance of CPSs depends on the design and modeling of WSANs.

The nature of CPS totally relies on applications. Different applications may have different network architecture. For example, in a application of fire handling, sensors, actuators, and controllers may be deployed over the surveillance area following a network architecture. The task of sensors is to sense the smoke and report about fire occurrence to actuators and controllers [6] quickly. Then, the actuators and controllers may take further actions such as the actuators equipped with water sprinklers react for a fixed time.

The overall network performance of a CPS depends on the imposed communication protocols. Design of efficient communication protocols is one of the most prominent issues to enable optimized communication among devices. The communication protocols generally include Physical layer, Data Link layer, Network layer, Transport layer, and Application layer. However, design of Medium

Access Control (MAC) layer, Network layer, and Transport layer has been capturing attention of the researchers in literature. Design and modeling of these protocols while maintaining the quality of service (QoS) of network performance for CPSs are still in embryonic stage. To confirm reliable communication, these protocols should be designed considering the special features of CPSs such as device heterogeneity, dynamic nature of environment, and dynamic network topology. The functionality and capability of CPSs components such as sensors, actuators, and controllers vary according to the demand of applications. Hence, traditional MAC, Network, and Transport layer protocols of wireless sensor networks (WSNs) may not be well suited for communication over CPSs. For instance, the delay in transmitting data varies with different application requirements. In a fire handling application, quick delivery of data is needed. On the other hand, for an air-conditioning system that controls the temperature of a room, the transmission of data does not necessarily have to be quick [3]. While designing communication protocols, the transmission delay and reliability of data delivery process should be considered. Different devices incorporated in CPSs may have different requirements of data transmission.

As CPS integrate diverse devices and control the operation and actions among those devices, CPSs account for the necessity of efficient channel assignment. The heterogeneous nature of devices in CPSs demands multi-channel multi-radio communication in most of the cases. Another challenge is mobility management. Many CPSs such as vehicle management, efficient traffic control, and aircraft control include mobile devices. Mobility management in CPSs is totally different from traditional mobile system. CPSs integrate mobile devices with physical world which sometimes need human participation.

Cyber-physical systems typically demand communication over wireless medium. To connect multiple heterogeneous devices, efficient wireless channel utilization and energy efficiency over radio transmission are needed. In this aspect, efficient channel utilization can be achieved utilizing cognitive radio-based communication. Some CPSs integrate mobile devices such as smartphones with other devices such as laptop. For example, in a surveillance system, video footage is captured in real-time using sensors. Hence, a synchronized network is needed to control the integration among physical systems, humans, and the cyber space. Such network often requires scalability to maintain synchronization. To meet such requirement, cloud architecture is needed in CPS delivering computing powers. We can consider the communication for CPS as a chart mentioned in Fig. 3.2.

Here, we present several recent works pertinent to CPSs. We discussed about different layers of the architecture of CPS from different aspects of systems design. In Sect. 3.2, we describe the existing specialized protocols at different layers for CPSs such as MAC layer, Network layer, and Transport layer from the perspective of protocol design. Section 3.3 discusses about the issues of multi-radio communication for CPS. We provide the challenges and issues of mobility in CPS in Sect. 3.4. Section 3.5 outlines the efficient channel utilization of CPS using cognitive radio network. We illustrate the cloud architecture for CPS in Sect. 3.6. Finally, Sect. 3.7 indicates the future research issues and frontiers related to CPS.

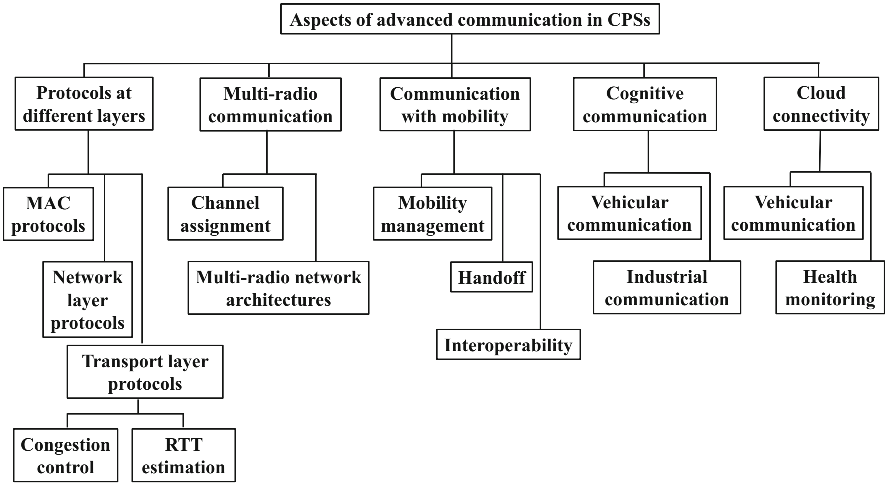


Fig. 3.2 Aspects of CPS communication

3.2 Specialized Protocols at Different Layers

Cyber-physical systems (CPSs) refer to the specialized form of embedded systems where computation, communication, and control are integrated with physical objects. CPSs are anticipated to be intelligently engineered systems having promising applications in diversified fields such as personal health care, medical services, intelligent transportation, scientific instruments, smart office, smart home, and public security. In CPSs, the interconnection of computing devices such as sensors and actuators is utilized in large-scale to complete multi-disciplinary tasks. Owing to the diversity of applications and computing devices, CPSs demand specialized communication protocols for computing devices to operate effectively and efficiently. Communication protocols generally consist of protocols of Physical layer, Data Link layer, Medium Access Control (MAC) layer, Network layer, Transport layer, and Application layer. Here, the impacts of protocols of Medium Access Control layer, Network layer, and Transport layer on network behavior of CPSs are worth of investigating in the literature. Hence, this section focuses on these protocols pertinent to CPSs.

3.2.1 Medium Access Control (MAC) Protocols

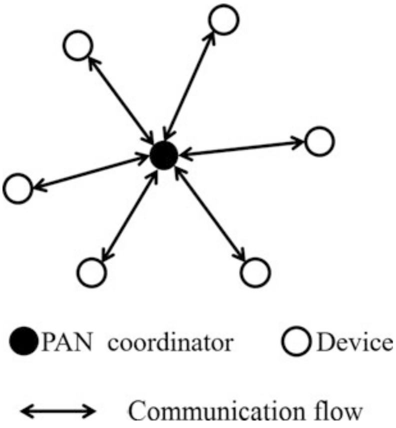
A suitable MAC layer protocol is required for interconnections among embedded devices in CPSs. IEEE 802.15.4 is the mostly investigated and widely adopted protocol in this regard [7]. IEEE 802.15.4 protocol is suitable protocol for short-range and low-power communication. Thus, IEEE 802.15.4 offers energy-efficient communication that often does not guarantee quality of services.

In recent years, low-rate wireless personal area networks (LR-WPAN) are being used extensively in many embedded applications. In these applications, IEEE 802.15.4 is being utilized as a wireless Medium Access Control (MAC) protocol. IEEE 802.15.4 has brought revolutionary emergence in LR-WPAN for its unique features [8]. IEEE 802.15.4 supports low data rate, low-power consumption, and low-cost wireless communication. The frequency band and other configuration of IEEE 802.15.4 are presented in Table 3.1. It also supports multi-hop network topology including star and peer-to-peer topology as shown in Figs. 3.3 and 3.4. In addition, IEEE 802.15.4 can operate on two modes, namely beacon-enabled and nonbeacon-enabled modes. In beacon-enabled mode, the device sends beacon frame periodically after beacon interval that can be configured [9]. IEEE 802.15.4 supports slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA) [8] protocol in beacon-enabled mode and unslotted CSMA-CA protocol in nonbeacon-

Table 3.1 Configuration of IEEE 802.15.4 [10, 11]

Property	Range
Raw data rate	868.0–868.6 MHz: 20 kb/s; 902–928 MHz: 40 kb/s; 2.4–2.483 GHz: 250 kb/s
Range	10–20 m
Latency	Down to 15 ms
Channels	868.0–868.6 MHz: one channel 902–928 MHz: up to 10 channels 2.4–2.483 GHz: up to 16 channels
Frequency band	Four PHYs: three for 868 MHz/915 MHz one for 2.4 GHz
Addressing	Short 8 bit or 64 bit IEEE
Channel access	CSMA-CA and slotted CSMA-CA
Temperature	Industrial temperature range −40 °C to +85 °C

Fig. 3.3 Star topology



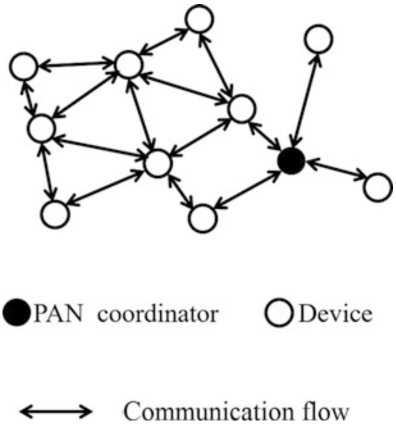


Fig. 3.4 Peer-to-peer architecture

enabled mode as the channel allocation mechanism. IEEE 802.15.4 is appropriate for devices with limited resources. However, it is not well suited when data rate is higher. Reason behind this incompatibility is that it does not exploit the notion of Request to Send (RTS) and Clear to Send (CTS) to avoid collision.

The basic functionality of CPSs is based on wireless sensor and actuator networks (WSANs) [4, 5]. WSANs refer to a generalized form of wireless sensor network (WSNs), which includes deployment of sensors as well as actuators. IEEE 802.15.4 can be exploited in WSANs and hence in CPSs. One-hop star network [7] considering deployment of all the nodes in each other's transmission range is an example topology of such exploitation. The topology is presented in Fig. 3.5. Here, both modes of 802.15.4 can be utilized. Irrespective of the adapted mode, experimental results prove that default configuration of IEEE 802.15.4 cannot provide best network performance for CPSs applications in various traffic load. Default configuration refers to the frequency 2.4 GHz along with bit rate 250 Kbps. The results also reveal the fact that it is very difficult to obtain a single generalized IEEE 802.15.4 MAC configuration to ensure optimized network performance.

IEEE 802.11 is another MAC layer protocol, which is widely used in WSNs [12]. IEEE 802.11 supports two different access methods—distributed coordination function (DCF) and point coordination function (PCF). DCF is based on carrier sense multiple access with collision avoidance (CSMA/CA) mechanism. The functionality of CSMA protocol is that a device sense the medium before transmitting data. If the medium is found to be busy, transmission is deferred. If the medium is found to be free, the transmission takes place. IEEE 802.11 utilizes the notion of RTS/CTS to avoid collision. Hence, IEEE 802.11 is suitable for long-range, high-bandwidth, and high-power communication. For example, in environmental monitoring, sensors monitor condition of the environment and then the sensed information is processed by some local controllers. Afterwards, this resulting information is transmitted to a central controller. The communication from local sensors to central controller often demands high-bandwidth and high-data rate transmission. IEEE 802.11 can be utilized for such communication.

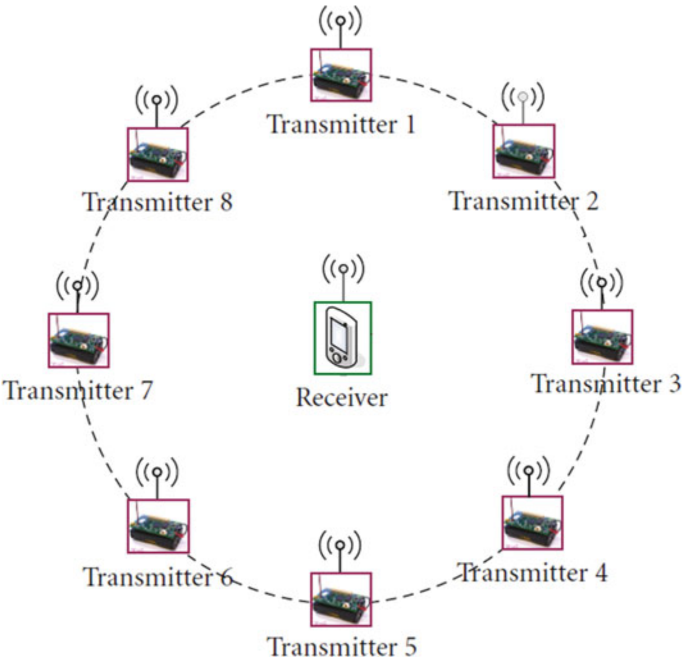


Fig. 3.5 Simulated star-network topology for cyber-physical systems [7]

3.2.2 *Network Layer Protocols*

Routing in Network layer is one of the most important aspects in data transmission over communication systems. CPSs demand efficient routing techniques to operate successfully. For efficient routing in CPSs, a number of challenges have to be addressed. For example, the network architecture itself varies for different applications of CPSs. This happens as devices such as sensors, actuators, and controllers are deployed at geographically different locations in CPSs. As a result, communication among these devices may be wired or wireless depending on the application requirements and position of deployment. Besides, these devices are not distributed in close proximity in many application scenarios. Hence, the communication may be single-hop or multi-hop. Moreover, mobility is yet another challenging issue, as some devices can be mobile and some can be static in a CPS.

In order to address the above-mentioned challenges, specialized routing protocols are needed for CPSs. Very few studies address the challenges in routing over CPSs to devise new specialized routing protocols. An example study [13] in this regard is based on IPv6 [14]. IPv6 is the most recent version of Internet protocol, which is an extension of IP version 4 (IPv4). Several structural updates in IP address have been made in IPv6 compared to that in IPv4. The most notable change is the use of 128 bits IP address in IPv6 instead of 32 bits used in IPv4, to support a large number of addressable nodes. Exploiting IPv6, multiple wireless sensor networks (WSNs) can be connected through the border routers [13]. The border routers operate based on IPv6 links. The main task of border routers is to translate IPv4 address to IPv6 address. Here, the overall network architecture can provide hop-by-hop forwarding and efficient routing along with the management of duty cycling. A deployment challenge for such architecture is the need to store 128 bits IP address and additional header information, which demands more storage compared to that needed for 32 bits address. Therefore, the drawback of using IPv6 is resource constraints, which is a major issue in CPSs. Nonetheless, as end-to-end communication between computing devices is required in CPSs, IP-based routing can be performed in CPSs. A network architecture [13] corresponding to such routing is presented in Fig. 3.6.

The requirements in routing techniques may vary owing to the requirements of specific applications of CPSs. One such requirements is data transmission to multiple destinations, i.e., multicasting. Multicast routing in CPSs is challenging because of two key issues which make CPSs different from traditional communication network. Firstly, the determination of uncertain destinations is required in CPSs. For example, in video streaming or file downloading, the destinations are the customers who are downloading the video clip or files [15]. Hence, the destinations are unknown and uncertain. Secondly, multicast routing demands the selection of optimal routing among multiple routing options. Conventional communication networks choose one set of paths for multicast routing which is called a routing mode. However, in CPSs, one routing mode may not provide best performance of system. Hence, multiple routing modes and switching among them is a challenging issue that needs special attention.

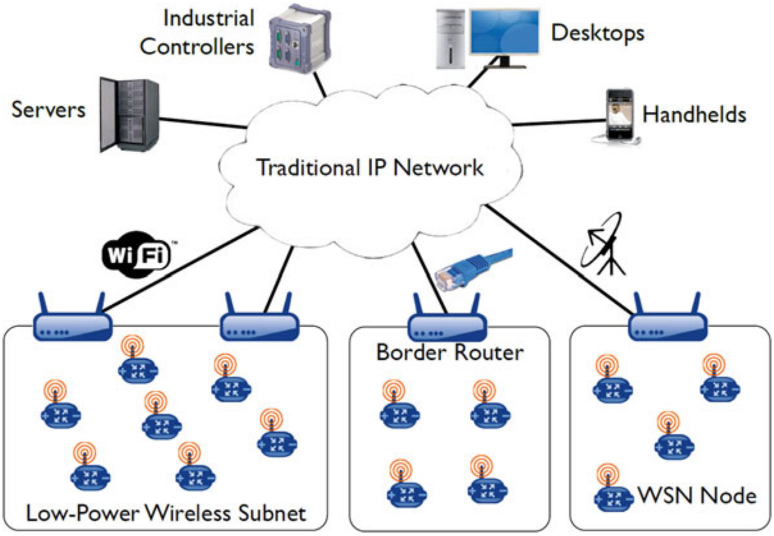


Fig. 3.6 Network architecture using border routers [13]

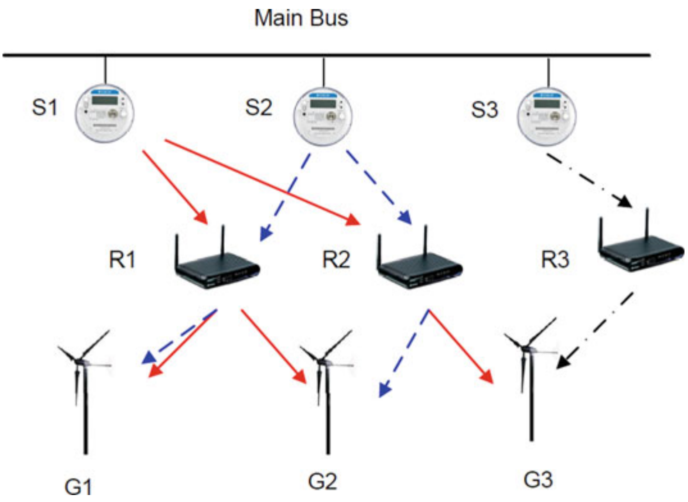


Fig. 3.7 Multi-cast routing in CPS [15]

An application of multicasting handling the above problems in CPSs is real-time voltage control in a smart grid [15]. Figure 3.7 exhibits an example scenario. Here, sensor, relay nodes, and distributed energy generators (controllers) are deployed in a grid that demands multicast routing. The sensors and controllers are integrated with communication interfaces assuming wired or wireless medium. Relay nodes are used as intermediate nodes to forward the observed information from sensors to controllers. Continuous data flow is considered from sensor to controller. Here, sensors monitor real-time voltage and send the sensed information to multiple controllers through relay nodes. Controllers evaluate real-time voltage and take necessary actions to stabilize the system. Besides, different routing modes are considered and dynamic switching among them is enabled. The main idea of proposed multicast routing is to determine a set of routing modes that can ensure stability of system dynamics and switch among these routing modes to achieve maximum system stability at a particular time. The connectivity of all sensors and controllers is stored in a matrix, which is called the feedback gain matrix. The connectivity is determined using bandwidth constraint. For each feasible connection between a sensor and a controller, the connection is added to the existing connections in the matrix, and thereby overall system stability is computed from the matrix periodically. For different connection scenarios, different states of matrix are determined and each state of connectivity matrix is considered as a routing mode. The routing mode with maximum system stability is selected for routing from sensors to controllers. The routing is demonstrated in Fig. 3.7 where one sensor forwards the sensed information to multiple relay nodes and hence to multiple controllers to deliver the observations accurately. Here, sensor $S1$ sends the data to relay nodes $R1$ and $R2$. $R1$ sends the data to controllers $G1$ and $G2$.

Many CPSs need the controllers to send information to sensors to take actions. For example, in a health care system, sensors sense information from physical environment (i.e., blood pressure) and send the information to controllers. Then, controllers process this information and send actions to the sensors. Thus, information is exchanged between CPS and physical environment forming a closed loop of actions. More precisely, CPSs can be considered as a closed loop system while sending and receiving information from physical environment. An example of study [16] of CPS considers CPS as a closed loop system. In this study, the whole distributed system is assumed as a combination of several dynamically formed subsystems [6]. The actions of these subsystems can be inter-dependent or totally independent based on the applications. The main concept of the work is that performance of whole system is determined based on the performance of each subsystem. Here, the nature of each subsystem is measured using a cost function which is called linear–quadratic regulator (LQR) cost function. LQR [17] is a mathematical algorithm, which is exploited for handling and running a controller controlling a machine or a process (i.e., an airplane, a vehicle, chemical reactor). LQR attempts to minimize a cost function with some weighting factors provided externally. The work [16] assume making one of weight factors of to depend on topology. The topology is determined regarding the whole communication network as an interconnection graph. Consequently, this topology-dependent LQR cost function is used to find the cost of each subsystem. The performance of overall system is then attained using cost of each subsystem. The routing and communication among devices are selected to improve the performance of the whole system. One major finding of this work is the fact that adding communication edges to the interconnection graph to find the topology sometimes may degrade the overall system performance.

In the work presented in [18], the authors propose an efficient event aggregation method utilizing proximity queries in a wireless sensor network. A framework termed as spatial and temporary processing (STP) is devised which reduces the cost for query registration by eliminating proximity events that are unnecessary. It also selects small number of aggregator nodes to send proximity alarms to the base node.

It is possible that, in many CPSs, underwater objects are used to perform certain tasks. Hence, under network communication architecture is an important issue in CPS. The study [19] proposes an energy saving tracking method which is based on local search for underwater wireless sensor network (UWSN). The main concept here is to keep active minimum number of sensors with a view to increasing network lifetime.

The research work done in [20] proposes an ant-colony meta-heuristics-based efficient collaborative routing mechanism. Here, best possible routing is constructed by making virtual circuits considering the load.

3.2.3 Transport Layer Protocols

CPSs consist of several embedded devices that are often deployed in an ad hoc manner over unpredictable environments. Therefore, communication among these devices may be single-hop or multi-hop pertaining to applications' requirements. As CPSs may be considered as wireless sensor and actuator networks (WSANs), they necessitate reliable and consistent data transmission to maintain robust communication among sensors and actuators. Hence, reliable Transport layer protocols are obligatory for CPSs. Existing Transport layer protocols may not be suitable for CPSs owing to their distinguished features, such as limited resource and low power. Problems that may generally arise in data transmission over CPSs can be categorized in two main aspects. First, packets may be dropped or lost owing to not having a suitable congestion control mechanism. Second, reliable data transmission may be interrupted due to not sustaining appropriate time synchronization (i.e., not having a good estimate of round trip time). Hence, this section presents these two aspects pertaining to CPSs in details.

3.2.4 Congestion Control Mechanisms

Achieving an optimized performance of Transport protocols over CPSs is always a challenging issue owing to the unique characteristics of CPSs. The notion of reliable data transmission in CPSs differs from that over other conventional networks. Here, performance of data transmission suffers for having a completely different type of a network with various embedded devices mostly connected in an ad hoc manner. Besides, the wireless medium in CPSs imposes lossy and non-deterministic data transmissions compared to mostly lossless and deterministic data transmission over wired networks. In addition, CPSs may contain different types of embedded devices resulting in heterogeneity. Hence, data transmission may have to adapt with both specialized low-bandwidth and high-bandwidth radios to meet requirements of the applications.

As CPSs often resemble WSANs, data transmission over CPSs frequently experiences propagation loss, multi-path routing, hidden station problems, etc. These problems rarely affect consecutive failures of data transmission attempts which is a considerable aspect for ensuring reliable data transmission. The main reason behind consecutive failures in data transmission is congestion in the underlined operating network. Congestion mainly occurs when two or more packets collide at the same time in a network. Congestion presents a classical obstacle to reliable data transmission.

A publish/subscribe-based middleware architecture, namely real-time data distribution service (RDDS) [21] enables reliable data dissemination over CPSs. This study utilizes the two traditional Transport protocols TCP and UDP for communication. Publish/subscribe architecture has gained popularity in recent distributed applications [22] because of its different features from conventional point-to-point architecture (i.e., client–server architecture). Here, producer (publisher) publishes events (sensed data on a topic of interest) and these events are broadcasted by server. Consequently, subscriber acquires this published data when needed while maintaining proper synchronization. Publish/subscribe architecture dynamically adds and removes publisher/subscriber which makes it a suitable communication system for a large-scale CPS. For example, in a search and rescue task during a fire accident in a building, the rescuing firefighters carry PDAs to gather data from nearby sensors to observe the dynamic condition of the building. Each firefighter's PDA can only acquire limited observations from nearby sensors. Hence, to get an overall information of the whole situation, all PDAs may have to combine the gathered real-time data by sharing synchronously [22]. These type of situation demand fusion of data from all sources (PDAs). Other examples of such CPSs are vehicular network, traffic control, and future combat systems.

The study [21] mainly focuses on reliable data transmission using two approaches. Firstly, for slow or unstable network, semantics-aware communication is exploited which refers to modeling of data streams utilizing lightweight physical models. In semantics-aware data stream modeling, same model is used for both publisher and corresponding subscribers to reduce computation and communication overhead. Secondly, to improve the quality of real-time data distribution and to achieve robustness, a reactive feedback mechanism at the publishers and the proactive feed-forward mechanisms at the subscribers are incorporated. Figure 3.8 shows a high-level architecture of RDDS. Here, each firefighter can participate as both publisher and subscriber to the sensor streams. T_{fire} is a topic of interest in which the generated events (data streams) are published by each entity (as a publisher) and each entity (as a subscriber) can also subscribe to the data collected from sensors. Quality-of-service (QoS)/quality-of-data (QoD) is maintained by a broker in a centralized manner. Transport layer protocols TCP and UDP are

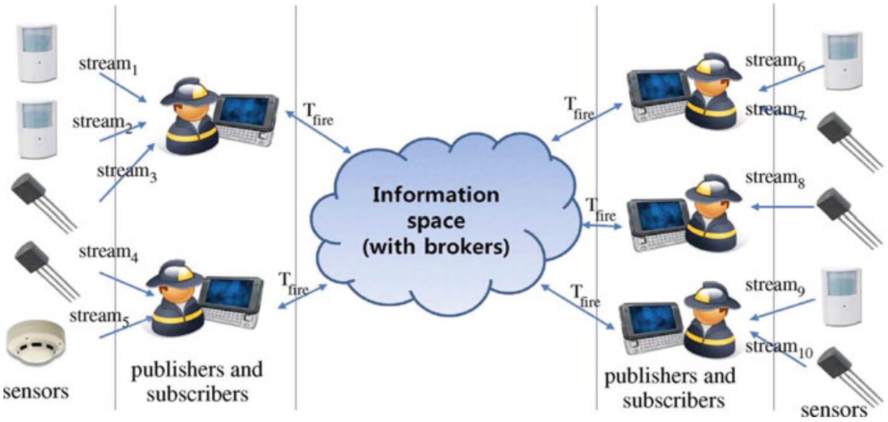


Fig. 3.8 Real-time data distribution service in cyber-physical system [21]

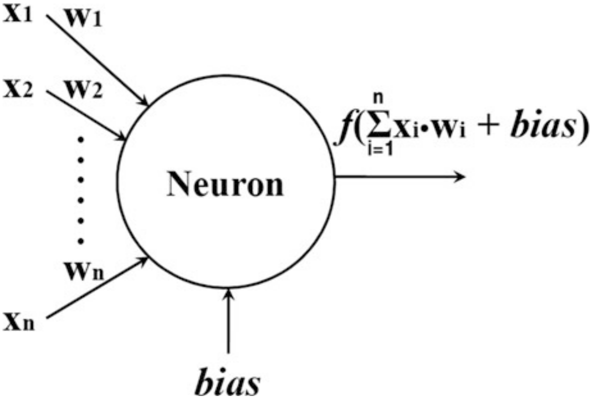
exploited for communication in lossy and unstable network. Here, packets are dropped following a random probability. The experiment results [21] reveal that UDP protocol is well suited for lossy communication as packet drop ratio with respect to exchanged number of messages remains stable while using UDP. On the other hand, while using TCP, the packet drop ratio increases with an increase in number of exchanged messages. This happens because UDP does not retransmit the lost messages, hence the total number of exchanged messages remains unchanged in lossy communication. However, while considering quality of data, TCP performs better than UDP. The quality of data degrades with an increase in communication load in UDP.

Maintaining importance of data is a crucial issue in congestion control for reliable data transmission over CPSs. Importance of data cannot be measured by assigning a static priority value or deadline [23]. It depends on dynamic and unpredictable state of the physical world. The sensing behavior of wireless sensor networks is widely distributed in many recent applications and hence, it demands accurate estimation of monitored physical measurements. For example, a CPS consisting of several wireless nodes along with base stations may be used to observe temperature and humidity distributions in a surveillance area [23]. The data can be sensed (sampled) with a fixed rate (i.e., once every second). Such type of sensing is called spatio-temporal as it provides a value in space and time. Transmitting this spatio-temporal data to base station using multi-hop routing sometimes results in congestion. Because of congestion, a node cannot transmit all the samples it observes to the next-hop node. Therefore, specialized congestion control mechanism is needed for collecting data with a view to maximizing the estimation accuracy of the data for such applications. This approach [23] considers different concurrent applications in the underlying CPS with different accuracy requirements. Here, relative importance of data is taken into account to minimize the overall estimation error. The data collected from different locations and at different times is summarized and utilized as a tool to control data transfer along with excluding congestion without increasing overall error in sensing the physical environment.

The main concept of this work [23] is that every node forwards its reading to corresponding base station regarding zero estimation error at starting. However, when congestion occurs, nodes experiencing congestion reduce their data transmission considering some estimation error to eliminate congestion. Hence, to eliminate congestion the minimal allowable estimation error is obtained. Here, each application is composed of several nodes along with a base station. Sensors sense data and send this data to base station. The connection among nodes is represented by a tree where the root of tree is the base station. Hence, sensed measurements are aggregated at intermediate nodes and are forwarded to parent node until it reaches to base station. Here, each application is assumed to accept a maximum tolerable error. The error is controlled locally in a neighborhood nodes to minimize the overall error. To determine the value of current error, the measurements at a node and the values accessible by its parent are compared. The data flow of a node is then controlled based on value of current error. The current error is kept less than or equal to the maximum tolerable error while controlling the output data flow. When congestion is detected, the value of maximum tolerable error is increased periodically until congestion is eliminated. Here, adaptive data summarization and aggregation are performed at intermediate nodes which ensure that the current error does not exceed the maximum tolerable error. This congestion control mechanism ensures more accurate estimation along with minimal communication overhead. However, for applications where the measurements of data need to be 100% accurate, this scheme cannot be applied because it allows some acceptable error to control congestion.

Determining the congestion window size is another important aspect while controlling congestion for reliable data transmission. Probability theory may be applied to do so [24]. Furthermore, an artificial intelligence-based congestion control technique [25] confirms the selection of optimal congestion window size over wireless mesh networks (WMNs) [26] in this regard. A wireless mesh network is a network where each node is connected to any other node. The distinguished characteristics of WMNs such as lossy and unpredictable environment in communication, data transmission without any base station, and similar pattern in traffic imposed by neighboring mesh nodes make reliable transmission in WMNs a challenging issue. These characteristics are also reasonable issues that may hinder reliable data transmission over CPSs. Here, neural networks (NNs) is used to control congestion which helps to omit the problems emerged from utilizing slow start, and congestion avoidance. NNs [27] refer to mathematical models that are used to represent the pattern of biological brains. NNs are composed of a number of neurons that unite with each other to execute some specific tasks. One or more inputs and a bias are processed by each neuron and thereby an output is generated based on the inputs. Figure 3.9 demonstrates the structure of a neuron where the output is a function of the sum of the weighted sum of the inputs and the bias. The proposed architecture utilizes multi-layer, feed-forward, zero bias NN with reinforcement learning to develop a congestion control mechanism. Multi-layer NN refers to a NN that have one input layer, one output layer, and multiple hidden layers. Reinforcement learning is a learning technique where the currently accessible inputs

Fig. 3.9 A typical neuron in NN [25]



are used to achieve an optimized output function. Feed-forward NN indicates a NN where direction of information is always forward, it means that the next output only depends on current inputs and independent of any intermediate outputs. Here, three parameters are selected as the inputs of NN and these parameters are utilized to obtain the output which is the optimal next congestion window size (cwnd). They are

– The number of consecutive timeouts,
– The number of duplicate acknowledgements (ACKs), and
– Current congestion window (cwnd) size.

The next cwnd size may increase, decrease, or remain fixed with respect to current cwnd size. The two inputs: the number of consecutive timeouts and number of duplicate ACKs are dynamically acquired from the performance of operating network. This congestion control mechanism is integrated with TCP which is called intelligent TCP (iTCP [28]).

The multi-layer NN is illustrated in Fig. 3.10 where one input layer, two hidden layers, and one output layer are shown. Three neurons are assumed as three individual inputs for consecutive timeouts (t_out), number of duplicate ACKs (dack), and current congestion window (cwnd) size. Then, the first hidden layer finds out the relative scale for increment, decrement, and no change of congestion window size. These three type of modifications represent three neurons (incr, decr, and same). Hence, these neurons calculate the relative weight of three types of update by taking inputs from each neuron in the input layer. These neurons also disseminate their outputs to the next hidden layer. The second hidden layer is used to find out the maximum order of update and the amount of that update. Here,

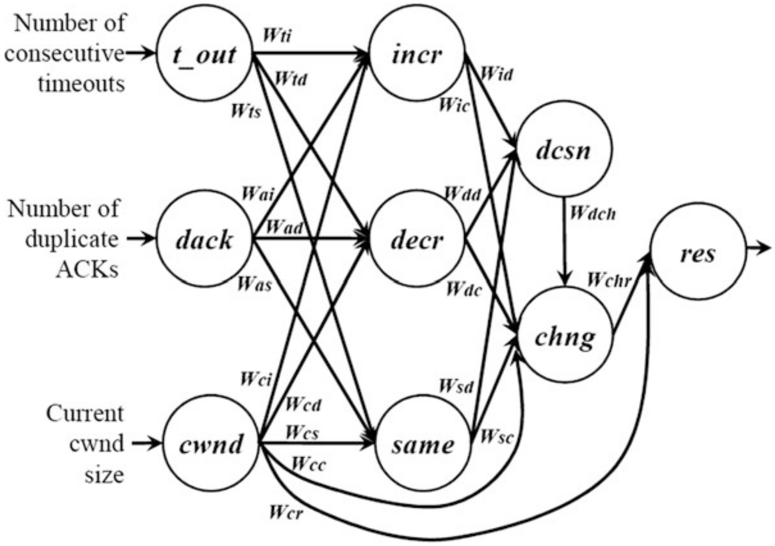


Fig. 3.10 Multi-layer structure of NN for determining the next congestion window size [25]

two neurons (decn and chng) are exploited to compute the desired two functions. The first neuron computes the maximum order of update which depends on the outputs forwarded by all neurons in the first hidden layer. Subsequently, the second neuron calculates the amount of update using current congestion window size and outputs of all the neurons from first hidden layer along with the maximum order of update from first neuron (decn). At last layer, only one neuron (res) is utilized to obtain the next congestion window size. The efficiency of this model depends on the appropriate regulations of weights and proper choice of the functions used in the neurons. The experimental evaluation of this scheme indicates that iTCP improves network performance in large coverage area of WMN with modest density.

3.2.5 Round Trip Time (RTT) Estimation Techniques

One of the most important parameters of timely and reliable data transmission is the estimation of round trip time accurately. Owing to special features of CPSs, a suitable round trip time estimation technique is essential to ensure reliable data transmission. Round trip time is the time delay between the transmitting of a packet and the receipt of its acknowledgement [29]. Estimating such round trip time ensures the successful and reliable delivery of data. If the acknowledgement of a packet is not received for too long, then the packet is considered to be lost and is retransmitted. Estimated round trip time is utilized to figure out when such retransmissions should take place. Accurate estimation of round trip time can remarkably improve the performance of underlying network.

A stateful round trip time estimation [30] scheme for wireless embedded systems utilizes an artificial intelligence (AI) technique called Q-learning [31] while considering resource constraint. This technique divides RTT estimation process into two independent cases. The two cases are as follows:

- Successful deliveries
- Packet drops.

Q-learning is one kind of reinforcement learning. It follows the nature of Markov process to take decisions optimally. In Q-learning, the effect of a decision is considered as a reward. After taking the decision, a state transition is occurred. Such transition to a particular state imposes a reward which is stored in a Reward-Matrix. Besides, another matrix is utilized which is called Q-Matrix that is updated based on the received reward and corresponding state transition. The Q-Matrix suggests optimum decision utilizing already taken decisions with a view to maximizing the next reward. In addition, it sometimes analyzes unexplored states to omit local optima. The key idea behind this approach [30, 32] is that two states (success and failure) are assumed for representing successful and failed transmission attempts individually. When sender receives acknowledgement then it implies a successful attempt and sender moves to a success state (S). Besides, when the retransmission timer expires, then it implies a failed attempt and forwards the sender to a failure

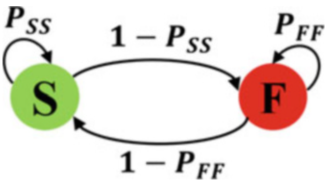


Fig. 3.11 State transition diagram representing success and failure of a wireless transmission

state (F). The state transition diagram representing success and failure is shown in Fig. 3.11. Here, P_{xy} indicates the probability of a transition from state x to state y. The probability of all transitions (P_{SS} and P_{FF}) is obtained using the corresponding source states. Thus, such state transition diagram follows Markov process. Here, exploiting this Markov process and Q-learning, the RTT in two different states is estimated. This RTT estimation (QRTT) is integrated separately in the TCP. The experimental results show that QRTT confirms significant improvement in network performance for wireless embedded systems.

Adjusting round trip time by detecting sudden changes in traffic load in the network is another approach for RTT estimation. The work [33] presents a RTT estimation approach by detecting the traffic change for heterogeneous communication networks. The unique characteristics of heterogeneous communication networks such as diversity in applications requirements, unpredictable condition of traffic load, and combination of wired and wireless links make the reliable data transmission of such networks a challenging issue. The traditional RTT measurements are generally computed from packet acknowledgements. Considering packet acknowledgements imposes delays which are caused by short-term traffic changes in the network. Such short-lived traffic can be regarded as noise while estimating RTT. The average RTT generally changes rapidly when the routing path experiences a long-lived traffic flow. Hence, it demands specialized process for filtering the short-lived (noise) and long-lived traffic load changes. It often requires that the device should react to the quick changes and estimate RTT more accurately to reduce packet loss and delays. However, first-order low-pass filter which is used by conventional TCP cannot be used for quick changes as it only depends on one parameter. A filter based on change detection can adapt for sudden changes in the high traffic flow. The main idea of this work is introducing a filter in RTT estimation depending on the change detection of traffic flow and detecting only the long-lived traffic changes while considering short-lived changes as noise. When network load increases depending on the application requirements, the RTT should be accurately adjusted to handle the increased network load, traffic flows, and sudden path changes. Here, an adaptive filter combining Kalman filter [34] and CUSUM algorithm [35] is introduced which detects the long-lived changes. Kalman filter [34] is a linear quadratic estimation algorithm which exploits a series of measurements monitored over a time period, having noise and other inaccuracies. It generates estimates of unknown variable with more accuracy. On the other hand, CUSUM [35] algorithm is a one-sided cumulative sum that is utilized for observing change detection. Here, Kalman filter and CUSUM algorithm provide an adaptive and flexible filtering which achieves significantly better accuracy in RTT estimation.

In general, when a transmitter sends a packet, it waits to receive the acknowledgement for that packet. If it does not receive the acknowledgement for too long, it will retransmit the packet again. If the receiver receives the retransmitted packet, then it will send the acknowledgement. In traditional TCP, when the transmitter receives this acknowledgement, there is no way to determine which transmission is being acknowledged which causes a major problem called *retransmission ambiguity* [29]. A study called Karn's algorithm [29] addresses the retransmission ambiguity problem. The key idea of this algorithm is to avoid the RTT measurements for retransmitted packets for estimating RTT. Here, when transmitter receives an acknowledgement for a packet that has been retransmitted (sent more than once), it will ignore any round trip time for this packet. There exists another metric called *retransmission timeout* (RTO) which is the time period that a sender has to wait for a sent packet to be acknowledged [29]. Retransmission timeout solely depends on RTT and is computed using RTT. RTO is calculated as a function of RTT in the conventional TCP. However, RTO does not only depend on RTT, it also depends on some other metrics (i.e., congestion window size). The work done in [36] finds the optimal RTO using congestion window size and RTT with a view to maximizing the throughput of network. Here, the intuition that the larger the congestion window size, the longer the optimal RTO [36] is taken into account for determining the RTO. The optimal RTO is computed as a function of RTT and congestion window size. The optimal RTO maximizes the TCP throughput which has been proved by experimental results [36].

3.2.6 Cyber-Physical Systems and Internet of Things

The integration of embedded computing devices, human and physical environment constitute a cyber-physical systems (CPS) in which these entities are connected by a communication infrastructure. On the other hand, the Internet of Things (IoT) indicates to the interconnection of heterogeneous end-devices which communicate through Internet. These end-devices refer to sensors, actuator, RFID, embedded computer, laptops, mobile devices, smartphones, smart devices, etc. IoTs are envisioned to be a technology that enables decentralized control among the interconnected objects. These objects are capable of sensing, processing, storing, and networking. These objects can also act as intelligent agents and can share information with people and other devices which can be part of an interconnected CPS.

Therefore, IoT-enabled CPS demands special concern considering different communication issues. There exist many communication protocols which are used to connect the things to the Internet. IoT enables end-devices to be directly connected to the Internet utilizing cellular technologies such as 2G/3G and 5G [37, 38]. Besides, these devices can communicate through a gateway to the Internet [39].

When the devices connect to the Internet through a gateway, it forms a local area network. This type of connection generally refers to the machine to machine (M2M) network using different radios such as Zigbee [40] (use the IEEE 802.15.4 Standard), Wi-Fi (use the IEEE 802.11 Standard), Bluetooth (use the IEEE 802.15.1), and 6LowPAN [41] over Zigbee (use IPv6 over Low Power Personal Area Networks) [39]. Irrespective of type of the wireless communication that is used to establish M2M network, all the end-devices should be able to provide their information (data) to the Internet. This task can be executed by utilizing a web server or by deploying cloud. For M2M communication in IoT, there exist some standards effort such as 3gpp [42] or ETSI.

The Third Generation Partnership Project (3GPP) was established in 1998 to develop specifications for advanced mobile communications by the team European Telecommunications Standards Institute (ETSI) [43]. 3GPP standardization provides a recent NB (narrowband) radio technology to support the advanced requirements of the IoT. It will support a large number of devices with low-throughput, increase indoor coverage, low-power consumption, and optimized network architecture ensuring security, quality of service, and radio access which are the basic requirements for CPS.

Considering the communication protocols, protocols for the end-user Application layer is a major concern as the end-devices are heterogeneous. To address different requirements of communication, various protocols have been proposed by the researchers such as Advanced Message Queuing Protocol (AMQP) [44], Message Queue Telemetry Transport (MQTT) [45], and Extensible Messaging and Presence Protocol (XMPP) [39].

The Advanced Message Queuing Protocol (AMQP) is a protocol that has been developed on the basis of the financial industry. The mechanism of this protocol is that it can use various Transport protocols; however, it considers a reliable transport protocol like TCP as an underlying protocol [44]. Asynchronous publish or subscribe communication with messaging is supported by AMQP. It has store-and-forward feature which is the main benefit of AMQP. This feature confirms reliability in such a state when the network is disrupted [46]. AMQP confirms reliability using different message-delivery options. For addressing different needs and conditions of CPS, AMQP can be a potential protocol for communication.

Message Queue Telemetry Transport (MQTT) is another protocol based on M2M communication. It is also an asynchronous publish/subscribe protocol like AMQP. Publish/subscribe protocols confirm the network bandwidth decrement. In MQTT, a broker acts as a server that contains topics [45]. MQTT confirms reliability by supporting different options for maintaining QoS level [39]. MQTT ensures low overhead compared to other TCP-based Application layer protocols [47]. MQTT brokers require username/password authentication for ensuring security.

There are many IoT platforms to address different requirements in different scenarios such as Amazon Web Services IoT Platform (AWS), Google Cloud Platform, and Microsoft Azure IoT Hub [48].

AWS was the first to turn cloud computing into an asset for IoT in 2004. It is a scalable platform which can provide support for billions of devices as well as trillions of collaboration between them. Besides, Google Cloud Platform is the one of best IoT platforms supporting web-scale processing, analytics, and machine intelligence. It offers security in the form of “Google Grade.” This IoT platform also has private global fiber network [48]. Another IoT platform, Microsoft is enabling Internet of Things through their cloud services. Like Amazon, Google, it also has some other beneficial services which include data analysis using machine learning.

Resource constraints is another prominent issue in IoT as well as CPS [49]. For efficient data management and analytics considering the limited resources, a widely used approach is fog computing. Fog computing is a hierarchical distributed architecture which is also known as edge computing. In fog computing, data, storage, computation, networking, and applications are distributed in an efficient way between data source and cloud. It extends the basic functionalities of cloud computing to edge network. Fog computing focuses on reducing the amount of data transmitted to the cloud for processing, analysis, and storage, thereby improving efficiency. Geo-distributed applications such as pipeline monitoring, wireless sensor networks to monitor the environment, mobile applications such as smart connected vehicle, connected rail, and large-scale distributed control systems such as smart grid, smart traffic light systems require efficient data management, analysis, knowledge of where data is computed and stored. These characteristics can be found within CPS and IoT. The main idea of fog computing is that the data processing is performed in a data hub rather than transmitting to the cloud for processing. Thus, it reduces the amount of data sent to the cloud for analysis. Hence, this type of computing can be a suitable solution for data management in CPS ensuring optimized resource utilization.

3.3 Specialized Multi-Radio Communication

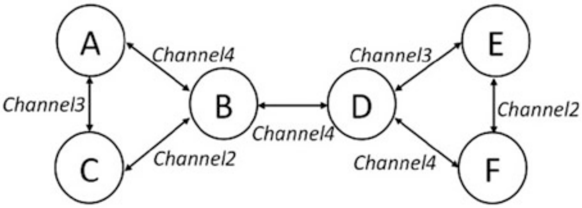
The functionality of CPSs is totally different from sensor networks. CPSs typically offer sophisticated systems of heterogeneous embedded devices. On the other hand, in sensor networks, homogeneous sensors are generally deployed in large amount. Thus, in CPSs, a device may have to connect and coordinate with another kind of device. For example, a sensor node has to communicate with actuators, controllers, and other types of sensors. Here, functionalities and channel allocation techniques are not same for sensors, actuators, and controllers. This is exactly where the necessity for multi-radio multi-channel technology comes into the play for CPSs. Hence, this section presents several existing channel assignment techniques that are suitable for CPSs along with the crucial factors that affect the channel allocation algorithm from the perspective of multi-radio communication.

3.3.1 Channel Assignment Techniques

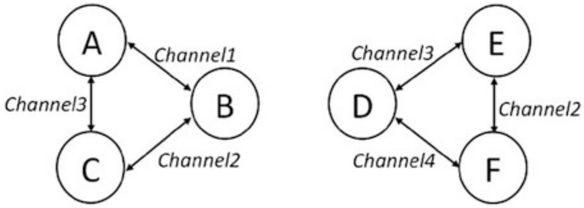
Channel assignment techniques for multi-radio communications are one of the most prominent concerns for ensuring optimized network performance. Channel assignment depends on various important issues. Some issues are presented below.

1. Connectivity: Connectivity is probably the most crucial issue for channel assignment algorithms in CPSs. Connectivity ensures data transmission among different nodes in a network. The importance of connectivity in a mesh network is illustrated in Fig. 3.12. Here, all the nodes are designed with two network interfaces utilizing four channels. The channel assignment technique in Fig. 3.12a confirms connectivity among all the nodes as the nodes form a connected component exploiting their available interfaces. However, if the allocated channel between *A*–*B* is changed from *Channel4* to *Channel1*, then *B* and *D* will not have any interface left to select a shared or common channel. As a result, the network is partitioned into two connected components as shown in Fig. 3.12b. Hence, this allocation of channel does not ensure connectivity over the whole network. In addition to connectivity, another important concern that needs to be investigated for data transmission is called *interference* [50].
2. Interference: When two nodes transmit data concurrently and their transmissions are sensed from a common position, their data transmissions get distorted at that position. This phenomena is called interference. Some efficient techniques have been developed to discover interference such as Protocol Model and Physical Model [51]. In Protocol Model, two transmission ranges are considered to detect interference—transmission range and interference range. On the other hand, Physical Model uses a threshold value at receiver for successful reception.

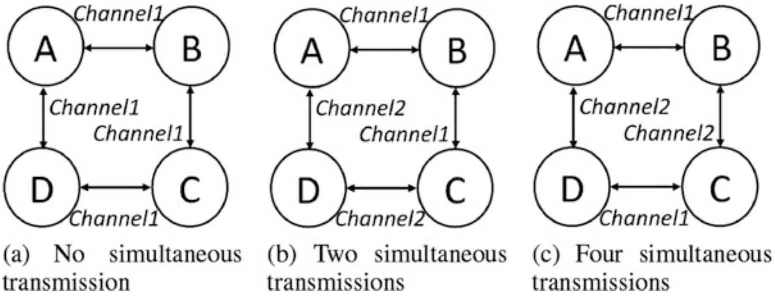
Fig. 3.12 Importance of channel allocation to ensure connectivity. (**a**) One connected component. (**b**) Two connected component [50]



(a) One connected component



(b) Two connected components



(a) No simultaneous transmission (b) Two simultaneous transmissions (c) Four simultaneous transmissions

Fig. 3.13 Illustration of channel diversity. (**a**) No simultaneous transmission. (**b**) Two simultaneous transmissions. (**c**) Four simultaneous transmissions [50]

The threshold value depends on the Signal to Interference and Noise Ratio (SINR). Physical Model is more applicable than Protocol Model in real scenario. However, the operation of Protocol Model is simpler than Physical Model. To accurately determine impact of an interference model, some important factors need to be considered such as path loss, signal reception, fading, and noise computation.

3. Channel Diversity: When all connected links of a node are exposed to non-overlapping channels, then this phenomena is called channel diversity. Channel diversity [50] is illustrated in Fig. 3.13. Figure 3.13a does not impose channel diversity as all the links are allocated to *Channel1*. However, Fig. 3.13b shows channel diversity as two links are assigned to *Channel2*, which enable two simultaneous transmissions for Node A and C. Finally, in Fig. 3.13c, all nodes can transmit exploiting two channels (*Channel1* and *Channel2*). Hence, channel assignment algorithm for CPSs should support channel diversity for allowing maximum number of simultaneous transmissions. A metric called *throughput* is considered to identify the efficiency of channel diversity. Throughput in a network is the average bit rate of transmissions. Most of the research studies focus on improving network performance by increasing throughput.
4. Dynamicity: Another important issue in channel assignment technique for CPSs is dynamicity. Dynamic nature of node activities and alivenesses in CPSs demands specialized channel assignment algorithm to cope up with any update in the network. Traffic condition, data flow, network topology, and physical environment are some parameters that can cause dynamic changes in the operation of CPSs. Hence, an efficient channel assignment algorithm should be designed for CPSs to make the whole network updated according to current status.
5. Distributiveness: The operation of CPSs can be controlled in centralized or distributed manner. Distributive channel assignment algorithms enable the embedded devices (nodes) to take own decisions of channel allocation. For efficient channel allocation, the devised algorithm should support distributiveness.
6. Mobility: Mobility is another important concern in CPSs. Mobile devices are exploited in CPSs depending on the application specifications. The channel

allocation algorithm should support efficient channel switching when a mobile device needs to switch channel because of the change in position to retain connectivity.

7. Fault Tolerance: CPSs may suffer from different types of faults such as fault in devices, link faults, and traffic congestion. Channel allocation algorithm should adapt to any kind of such faults through utilizing alternate channels to ensure connectivity.

There are some other criteria such as synchronization, scalability, stability, load balancing, utilization of fixed shared channel, and control overhead, which should be considered for efficient channel allocation algorithm for CPSs. There exist several channel assignment techniques that consider such criteria. A selected set of the techniques are presented below from the perspective of CPSs.

- Semidefinite programming (SDP)-based channel assignment approach [52] utilizes a centralized and static manner for channel allocation in multi-radio networks. The main idea behind this approach is that the channel is chosen randomly from *k* orthogonal channels while confirming minimum interference. Here, each device is equipped with multiple interfaces. Hence, a channel is allocated to both interfaces of each link to minimize interference conflicts. This technique ensures optimal channel assignment, though it is only applicable for orthogonal channels and does not consider traffic condition, external interference, etc. Nonetheless, simplicity and flexibility of this scheme make it an effective solution for data transmission in CPSs.
- Skeleton assisted partition FrEe (SAFE) [53] exploits randomized channel allocation in a distributive manner with a view to ensuring network connectivity over multi-hop communication. It considers two status of networks: the number of available channels and the number of available interfaces. SAFE allocates channel randomly if the number of usable channels is less than the double of accessible interfaces. When this condition is violated, network connectivity may be interrupted. In such a case, a connectivity graph called skeleton is formed and channels are reallocated to the edges to confirm connectivity. Here, the channel allocation randomly selects channel for all interfaces except one. That one interface is assigned as an edge of the skeleton. It also confirms channel allocation considering dynamic topology and increase in deployment. SAFE channel allocation is demonstrated in Fig. 3.14. In this scenario, each node has three available channels and two wireless interfaces. The channel allocation

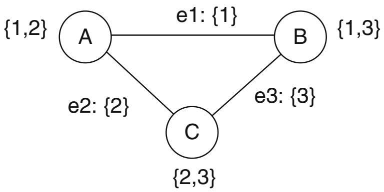


Fig. 3.14 Illustration of channel allocation in SAFE channel allocation scheme [53]

shown in Fig. 3.14 ensures no interference among links. However, this technique does not consider or impose any priority for the links.

- Adaptive dynamic channel allocation (ADCA) [54] is a dynamic channel allocation technique that operates over mesh topology. The technique considers two metrics of network performance for channel allocation—throughput and delay. Here, channel allocation is performed with a view to reducing delay and without diminishing throughput. These considerations make it a potential solution for channel allocation in CPSs having mesh topologies. In ADCA, each node maintains two interfaces—static and dynamic. The dynamic interface can switch channels. On the other hand, the static interfaces use fixed channels. ADCA supports maximization of throughput while allocating channels for static interfaces. Besides, dynamic interfaces choose channels by keeping queue for each neighbor. Priority of each neighbor is evaluated based on corresponding queue length and waiting time. Here, each node selects a channel in two steps. Firstly, each node selects a neighbor based on the priority, and secondly, channel negotiation is performed if the queue length is less than a specified threshold. This scheme supports negotiation of shared channel among more than two nodes at each time interval, which confirms reduced delay. Nonetheless, ADCA is not suitable for extreme traffic load, since the queue gets overloaded in the presence of extreme traffic load. In such cases, channel negotiation gets abandoned.
- Multi-radio breadth first search-based channel assignment (MRBFS-CA) [55] assigns channels over mesh topology. In this technique, a channel assignment server called CAS performs the channel allocation for the whole network periodically and informs all the nodes about the allocation. For channel assignment, CAS utilizes Protocol Model [51] to estimate interference assuming interference range as double of transmission range. It supports two different types of radios, namely default and non-default radios. This approach selects the default radio while ensuring minimization of interference between own network and external networks. In non-default radios, CAS constitutes a multi-radio conflict graph (MCG) [51] and applies BFS channel allocation over the MCG. To do so, both radios are differentiated according to the minimum hop counts from CAS and expected transmission time (ETT). It confirms connectivity along with minimizing interference. However, it causes high control overhead owing to broadcasting from the CAS and sending beacon messages from all nodes. The considered features of this technique also prevail in operations of CPSs. Hence, this scheme can be used for channel allocation in CPSs.
- Existing channel assignment techniques for multi-radio mobile ad hoc networks can also be utilized for channel allocation in multi-radio mobile CPSs. For example, Q-learning-based channel allocation [56] can be used for such CPSs. This channel allocation technique supports distributive and dynamic channel assignment. Here, nodes or agents are enabled to make decisions through analyzing their experience from an unknown environment enabling reinforcement learning [57]. It also obtains random and new operating points periodically going beyond the previous experience. The overall experience is maintained by a matrix called Q-matrix. Here, each decision taken by the agent is evaluated from its outcome

and the Q-matrix is updated accordingly. This technique was originally designed to ensure energy efficiency in sensor network and the decisions are evaluated in terms of energy efficiency. As it supports channel allocation with unknown characteristic of the environment, it can be utilized for assigning channels in CPSs. Here, the metrics of evaluation can be customized according to the CPS application requirements. Such metrics can be the number of transmissions, interference, connectivity, throughput, etc. The technique generally performs well for this flexible nature though it may not provide stable connectivity. Reason behind the instability of connectivity is that this decision making is performed at each individual node rather than performing any overall decision making for the whole network.

- Another approach for multi-channel allocation is channel assignment based on probability [58]. It offers a distributive and dynamic probabilistic channel usage-based channel allocation for wireless ad doc networks. This scheme keeps individual queues for each of the accessible channels. Here, channel is classified into two categories—fixed and switchable. Here, data reception is performed using fixed channels and data transmission is done using switchable channels. The persistence of channel allocation in fixed channel is longer than that in switchable channels. The underlying assumption of this technique makes it suitable for multi-radio channel allocation in CPSs applications having the capability of operating with fixed and switchable channels. In this technique, a node assigns channels randomly to all its interfaces and it updates the channel of fixed interfaces to a less utilized channel with some probability. This update occurs when the number of users on the common fixed channel grows larger. To keep this information, each node maintains a channel usage list and periodically updates it while exchanging the list with neighbor nodes. On the other hand, the switchable interfaces are assigned channels based on the oldest packet of the queue. The technique provides connectivity by using these switchable interfaces; however, it does not concede any interference cost while assigning the channels.

3.3.2 Multi-Radio Communication Architectures

CPSs demand specialized multi-radio multi-channel communication architecture to establish and maintain connectivity with the network. Most CPSs consist of heterogeneous devices. Moreover, network topology is also dynamic. This section describes some existing specialized multi-radio multi-channel architecture that can be utilized for many CPSs application for effective operation.

Energy efficiency is one of the most prominent issues in facilitating communication in CPSs. We know that radios of sensor nodes consume significant amount of energy. Since data transmission in CPSs is generally dynamic and unpredictable, hence data transmission can be frequent or infrequent based on application requirements. For infrequent data transmission, energy efficiency can be achieved by lowering the sleep-mode power consumption of multiple radios. In such scenarios, IEEE 802.15.4 is a potential solution since it supports low sleep-mode power consumptions. However, IEEE 802.15.4 is not appropriate for frequent data transmission. On the other hand, 802.11 supports frequent data transmission through its high bandwidth at the expense of more energy consumption. In addition, 802.11 can serve as a transmission-efficient radio since it consumes lower energy per bit of transmitted data than that of 802.15.4 radio. Nonetheless, 802.11 has high sleep-mode power. In order to handle the above-mentioned problems of both radios, specialized multi-radio techniques are needed that can combine the best qualities of both 802.11 and 802.15.4 radios.

In the study presented in [59, 60], an energy-efficient multi-radio architecture called Backpacking is proposed combining both short-range radio 802.15.4 and long-range radio 802.11. This study exploits energy efficiency of 802.11 radios from the perspective of data transmission and energy efficiency of 802.15.4 radios while remaining in non-active mode, even though both the types of radios work over the same frequency band (2.4 GHz ISM band).

The proposed architecture considers high data rate sensor networks. Here, 802.15.4 radio is utilized for transmitting sensed data from sensing nodes. The data sensing tasks are performed utilizing sensor nodes called originators. Originator nodes support only one 802.15.4 radio. After sensing the data by the originator nodes, data is accumulated and forwarded to the base station by another type of node called accumulator. These accumulator nodes are equipped with both 802.11 and 802.15.4 radios. Here, accumulator nodes receive or accumulate sensed data from originator nodes using 802.15.4 radios, and they forward these accumulated data to a base station using 802.11 radio. Hence, accumulated data gets backpacked using 802.11 radio. The network architecture considered in [59] is demonstrated in Fig. 3.15. Here, the hierarchy of collecting sensed data and sending the data to a base station is shown using 802.11 and 802.15.4 radios. There is an optimal deployment [59] density of the two radios for a network. A cross-layer mathematical estimation model[1] determines the density and provides a delicate balance of using both types of radios.

Another important concern in multi-radio communication is the heterogeneity of multiple radios. Heterogeneous multi-radios can improve the overall network performance in wireless networks. The characteristics of multiple homogeneous radios cannot always be adopted directly due to having different transmission ranges, bandwidths, and power consumptions. Thus, heterogeneous multiple radios come with some problems and challenges. The key design challenges of heterogeneous multiple radios are as follows [62]:

- Utilization and synchronization of multiple heterogeneous radios from a single device is a challenging task.

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[1] A perfect modeling for such architectures is known to be infeasible [61].

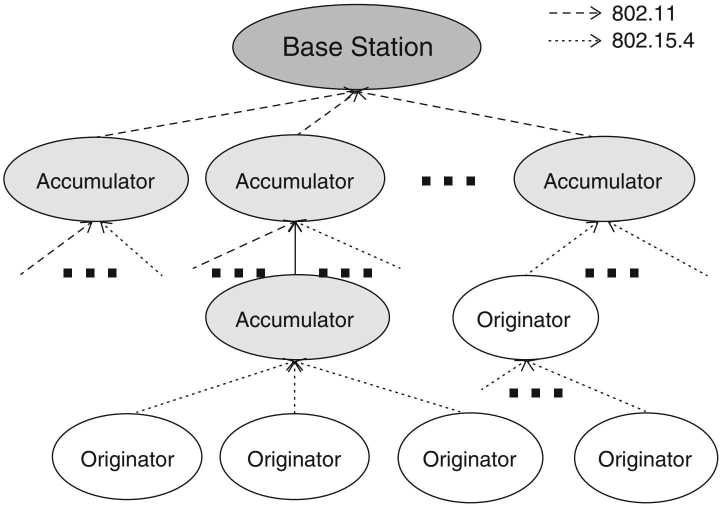


Fig. 3.15 Network architecture utilizing two different types of radios [59]

- For simultaneous utilization of multiple heterogeneous radios, the notion of data splitting comes into play. The optimal mechanism for efficient data splitting over multiple heterogeneous radios is another challenging task.
- How data splitting will be performed by the layers of the communication protocols is also another challenging task.

The above-mentioned challenges have been investigated in the literature [62]. It has been found that the radio with highest-bandwidth in the heterogeneous multiple radios performs well for low or moderate data rate multi-hop communication [62]. Nevertheless, this radio may show bad performance in high data rate applications. Considering these aspects, an approach [62] is proposed to perform concurrent activation of lower-bandwidth radios along with the best one to enhance network performance. Here, the activation of lower-bandwidth radio can improve the network performance in greater proportion than what the capability of lower-bandwidth radio adds with respect to the best one.

Another key issue is that the partitioning of data over multiple simultaneous radios demands optimized partitioning to achieve the best network performance. Here, optimal data splitting is determined taking into account some other factors such as network topology, data flow characteristics, and radio attributes. Furthermore, among multiple heterogeneous radios, the optimal point of data splitting changes according to the optimization parameters that can be configured by the application. Throughput, end-to-end delay, packet drop ratio are examples of such optimization parameters. Nonetheless, the optimal point of data splitting also depends on link quality and nature of a flow. Thus, the optimal data splitting over multiple heterogeneous radios can be achieved considering these aspects after selecting the optimization metrics from the application, which necessitates some user-level customization. This data splitting technique from application level is termed as simultaneous activation (SiAc) [62]. This approach of data partitioning among multiple heterogeneous radios provides a potential solution for data transmission in CPSs. Similar other data splitting techniques from application level also exist (for example, SymCo [63]).

The channel assignment problems have been jointly investigated with congestion control, which is suitable for multi-radio CPSs experiencing data rate transmission problems. In such a scheme [64], each deployed node regulates injected rate dynamically to achieve the optimal network utility. Here, the injected rate of a node is the rate at which packets are injected in the network. To achieve the optimality, the congestion control is considered as an optimization problem to maximize network performance or utility. The network utility [65] is obtained from the perspectives of metrics in multiple layers such as power consumption, delay, link data rate, and end-user data rate. The optimization problem is formulated mathematically by analyzing the network behavior and constraints for maximizing the network utility. The network utility maximization problem is developed through mixed-integer nonlinear programming (MINLP).

3.4 Communication over Mobile Cyber-Physical Systems

Mobile cyber-physical system (MCPS) is a subcategory of CPSs in general [66]. The inherent distinguished feature of MCPS is mobility. Similar to the notion of CPSs where sensing the environment and reacting to sensed data are parts of processing and computation tasks, MCPS brings to the table non-stationary models of cyber-physical world. An example of a popular MCPS comprises smartphones [67]. Smartphones today are blessed with a physical dimension that allows them to be carried around in users' pockets. They have multi-core processing powers, considerable amount of data storage capability, multi-radio communication ability, and the support of high-level programming languages. However, not all MCPSs are blessed with such computing processes. Thus, for MCPSs with power consuming operations, tuning up variables and parameters such as network throughput, power consumption in radio operations, and data sensing and processing delays are very crucial.

MCPSs are different from conventional embedded mobile systems from the perspective that they are more human-centric demanding human participation and interaction [68]. For example, in MCPSs, human interventions process sensed data and make interpretations from it while the systems continue interacting with the physical world for us. Although the basic cycle of operations in MCPSs may appear to be similar, their applications are different. Moreover, the swarm of devices in an MCPS operating in a particular environment is different and heterogeneous compared to that operating in other networks [69, 70]. Consequently, this section discusses on MCPSs from three important aspects pertaining to mobility, namely mobility management, mobile handoff, and interoperability between carriers.

Before proceeding with discussions based on MCPSs, a general discussion regarding the state-of-the-art terms such as wireless mesh networks (WMNs), wireless sensor network (WSN), and mobile ad hoc networks (MANETs) is warranted. Although MCPSs, WMNs, WSNs, and MANETs are not necessarily completely different concepts, there still remain some important distinctions.

Ideally, the wireless ad hoc networks can be classified into the following three categories:

1. **Wireless mesh networks (WMNs):** The idea behind WMNs is to maintain a mesh topology over interconnected wireless nodes. IEEE 802.11 radio is mostly used because of its high-bandwidth and long-range networking capability. IEEE 802.11s is a new multi-hop networking technology specifically targeting mesh network topology. WMNs are self-organizing and self-configuring, which in turn reduces the setup time and maintenance cost. Because of low deployment cost, WMNs are preferred over single hop wired connection over a large area network. Moreover, because of alternative route to source–destination paths, the overall network reliability increases. WMNs also provide cross-domain interoperability via multi-point to multi-point architecture. Thus, interoperability among popular technologies such as Wi-Fi, WiMAX, Zigbee, cellular, and Bluetooth is possible [71].
2. **Wireless sensor network (WSN):** WSN is a network architecture of sensor nodes. Sensor nodes sense from environments, detect events, take actions immediately, or send data to a base station for interpretations. Some popular applications of WSNs are environment monitoring, industrial monitoring, smart home monitoring, etc.
3. **Mobile ad hoc network (MANET):** Wireless nodes are free to move. As a result, MANETs function over a dynamic topology with limited bandwidth constraints and variable link capacity. Some important applications and examples of MANET are battlefield communications, vehicle ad hoc network (VANET), internet-based mobile ad hoc network (iMANET), etc.

While WMNs, WSNs, and MANETs are not necessarily disjoint in core concepts, the recent trend of research and applications is mostly based on interactions between machines and physical world. In the following, we take a stride at understanding some differences between WSN, MANET, and MCPS [72].

- Routing capabilities and requirements are different for WSN, MANET, and MCPS. For example, MANET supports either unicast, multicast, or broadcast. On the other hand, WSN supports patterns such as query and response. In case of MCPS, several WSN may work together to form a system of interconnected sensor nodes. Cross-domain communication is also frequent in MCPS [73]. Such an example is the control of water gates of a dam through observing readings from several rain meters and water level measuring sensors [72]. In [74], a data collection approach is proposed for WSN considering mobile nodes. Here, instead of locating the exact mobile node, a node which is located in close proximity from exact node is selected to minimize the tour length.

- Mobility of nodes in case of MANET is arbitrary. Although the general norm of WSN is less mobility to stationary connected nodes, however, some controllable and uncontrollable mobility has also been studied [75]. In case of MCPS, it is well assumed that mobility is a requirement. The control state could either be human controlled or automated.
- Considering the routing capabilities and the possibility of having mobile nodes, MANETs have a random network formation. Contrary to the requirements of MANET, WSNs are more application and field specific. We already know that MCPS supports cross-domain communication. Hence, internet plays a dominant role in connecting cross-domain applications in MCPS.

3.4.1 Mobility Management

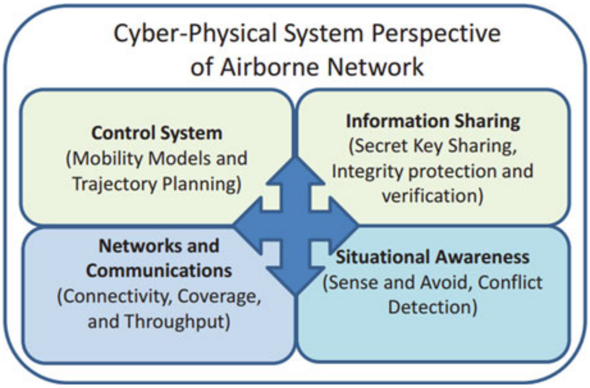
One of the key aspects of MCPS is research based on mobility types and models. Mobility modeling help researchers understand and define different aspects of mobility related problems. Since the network architecture of MCPS is closely related to mobile ad hoc networks which support microscopic view on mobility modeling, we resort to a similar view on MCPS. In this section, we will provide an overview of different types of cyber-physical systems, such as vehicle cyber-physical systems, airborne cyber-physical systems, and waterborne cyber-physical systems.

3.4.1.1 Airborne Cyber-Physical Systems

Airborne cyber-physical system (ACPS) is an old research topic. However, recent advancement in aviation and air warfare has led to massive investment in airborne cyber-physical systems. In ACPS, flight-paths, maneuver analytics and geometries, and multi-mode resources including ground-based nodes and control stations form the physical component. The cyber component consists of networking and communications, with computations and processing often off-loaded to cloud architecture [76, 77]. Figure 3.16 shows basic components and design principle of airborne cyber-physical systems.

An important component of ACPS is airborne network, or in other words, airborne MANET. It primarily consists of several subnets of nodes making connections with adjacent nodes while flying through a sea of virtual nodes [76]. Figure 3.17 shows an illustration of ACPS. It has few airborne and ground nodes. The requirements for ACPS are unique—mobility models should take into account smooth turns at high altitude, data transmission assurance, data authenticity, and data integrity. The purpose of mobility model is to provide a framework for studying connectivity, network performance, and decide which routing protocol performs optimally, given the constraints [78].

Fig. 3.16 Design principles of cyber-physical perspective of airborne network [76]



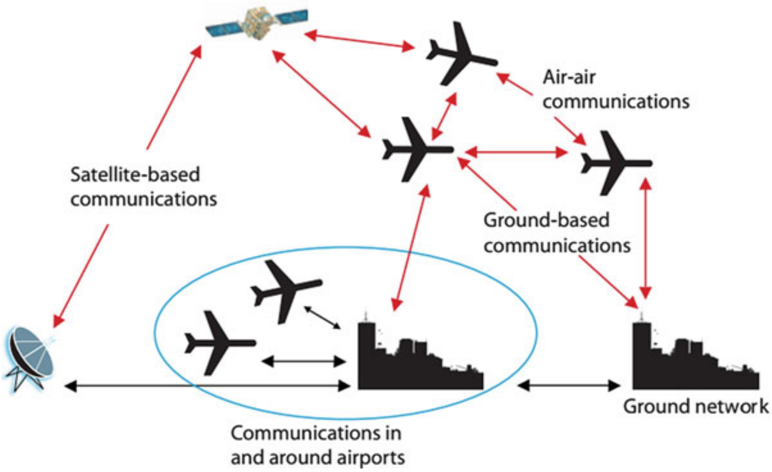


Fig. 3.17 Illustration of airborne network depicting cyber-physical systems [76]

Airborne objects tend to preserve motion in a straight line, that is, they maintain the same heading speed. In case they have to make a turn, it follows part of a large circular path [76]. In order to estimate path of an airborne vehicle, such as a jet fighter plane or a normal passenger plane, a mobility model should be able to capture such smooth turns. Some mobility models have been well rehearsed in literature. Random direction (RD) [79] and random waypoint model (RWD) [80] are two such models that theoretically come closer to airborne movements. In RWP model, the agent assumes a random destination. When it reaches to a particular destination, it pauses and then starts for the next destination. The non-uniform spatial distribution of nodes in RWP results in higher density towards the center and almost zero density towards the border region. Such a property is not desirable all the time in case of ACPS. Remedy to such non-uniformity in RWP is the random direction model. This model exhibits less fluctuation in node distribution. Above such theoretical studies, realistic models need to be developed in order to simulate and estimate ACPS.

3.4.1.2 Maritime Cyber-Physical Systems

The maritime cyber-physical systems consist of the interaction between physical processes and the cyber world. The idea of cyber-physical systems in maritime is to provide smart, efficient, and robust communication platform at sea [81]. Until recently, plenty of wireless infrastructures have been put up to support maritime communication. For example, the Wireless-Broadband-Access to Seaport (WISEPORT) in Singapore exploits WiMAX and fourth generation LTE in its sea area [82]. In maritime cyber-physical systems, vessels, buoys, ships, and coastal authorities can form a system of mesh network and exchange data from vessel-to-vessel or vessel-to-infrastructure [81]. There are ample research studies in the literature offering cognitive radio-based communication as an alternative to long distance multi-channel interference problem in maritime communication. Discussion on cognitive radio-based communication is available in Sect. 3.5. There are very few to no literature review on mobility models in maritime environment and conjointly linking cyber-physical systems with it.

3.4.2 Handoff in Mobile Cyber-Physical Systems

Handoff is an important attribute in mobile systems that need to maintain seamless connection to an end-point. Handoff or handover is the process of maintaining a user’s active session even though he/she seems to have changed his/her current point of connection from one network to another network [83, 84]. In cellular network, when call is in progress, it means that the call has acquired a channel. When the call is complete, the channel is released. In-progress calls maintain a direct link with the nearby base stations, which forms a virtual area called cell as a region of coverage. When a mobile unit crosses over this cell into a new cell, it needs to switch its link to another base station and new frequency in order to continue [85].

Handoffs can be two types depending on how they were originally connected and how they are now connected to the new base station. Figure 3.18 shows two types of handoffs. Horizontal handoff supports the connectivity handover between two network base stations following similar network protocol stack [86]. For example, in case of cellular network, when a user communicates over his cell phone while moving in a car, horizontal handoff takes place. Vertical handoff takes place when the point of connectivity switches over between two networks supporting different network protocol stack. For example, a person switching over from cellular data to Wi-Fi while browsing internet [86]. The first step of handover is the initiation of the process, i.e., mobile node collects data regarding current link state, received signal strength (RSS), throughput, jitter, etc. These data help mobile device take a decision. Next, the mobile device executes the decision. If it has to execute handoff, then network authentication and authorization takes place to switch user’s context from current state to a new state [83].

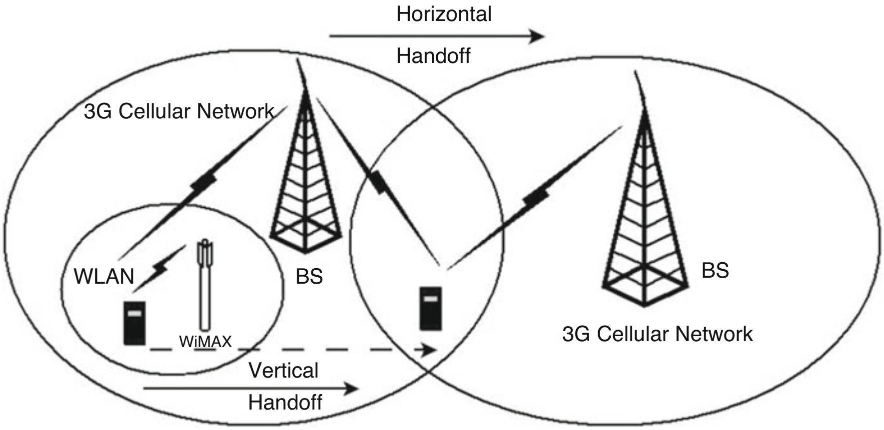


Fig. 3.18 Handoff in cellular network [83]

Currently, mobile handoff is mainly required for vehicular movements of mobile nodes. Such movements could be due to airborne vehicular movement, roadways vehicular movement, or high speed train movement. In case of high speed vehicular movement, there are three cases where problems regarding mobility persist [87]. First, frequent handover causes frequent re-selection of cells, hence communication quality will be disrupted. Second, Doppler frequency shift causes delay and failure in handover initiation and handover attempts, respectively. Finally, if the mobile node has a reasonably large mass or size, then it is probable that the mobile node will suffer from multipath fading. Hence, propagation modeling comes into the scenario.

3.4.3 Interoperability in Mobile Cyber-Physical Systems

The idea of interoperability is very crucial in terms of mobile cyber-physical systems. Current cyber-physical systems are designed and deployed to perform crucial tasks, for example, event-based environment monitoring, patient health care monitoring, industrial process automation, etc. Different devices are being used which constantly interact with physical world. They need to extract information from the interaction with physical world and get an interpretation from a computing or processing unit, or receive an action through human intervention. Despite the challenges prevalent in mobile sensing nodes, interoperability is yet another challenging domain. Interoperability demands inter-dependency and interconnection between different entities in an ecosystem of cyber-physical systems.

There are three important challenges in mobile cyber-physical systems interoperability [88].

1. **Heterogeneous sensor platforms:** The diversity in sensors and their platforms make programming those sensors complex and complicated. If we increase precision and granularity of sensor data reading, the effective bandwidth of the data extracted from the sensor increases. Moreover, since these sensors are mobile in nature, they are definitely battery based. Hence, power resource constraints is another concern while choosing sensing platforms. One way to solve heterogeneity in sensing systems is to provide abstraction to the gathered data. Essentially, some transformations may be applied to the raw stream of sensor data to produce a semantically meaningful stream. For example, instead of simply storing Wi-Fi RSSI data at each location for indoor localization, one can store corresponding access point location, their transmit power level, and their physical location (latitude–longitude). The latter can be termed as virtual sensor reading.
2. **Heterogeneous network:** While setting up a network, say WSN or WMN, a pool of commercial routers need to be bought and set up in our testbed. Commercial routers for Wi-Fi or other radios are less reliable in terms of fine tuning their transmit power level and received power level. Consider the case of Wi-Fi networks. Wi-Fi networks are susceptible to variable RSSI values in different conditions. With varying traffic load, the level of contentions and congestions will also be different. Among possible solutions to such dynamic problems, alternative measures to capturing data can be taken. For example, if the purpose of Wi-Fi network is to transmit data for localizing victims in disaster affected scenarios, a WSN can send audio data that semantically can explain the situation at that instant, such as loud noise, coughing, explosions, too loud, and too quiet for a long time.
3. **Heterogeneous applications:** Deployment of mobile cyber-physical systems is often preceded by extensive simulation and testing. For that, many software simulators are available to simulate events before considering real-life deployment. Such simulators are domain specific. Interoperability of heterogeneous applications can be reached by building multisimulation tool software. The idea is to reuse a simulation model for varying purposes.

One way of achieving network interoperability is to introduce a basic redundancy scheme [88]. In this system model, each device carries a cache to store and bundles for itself and others. When devices come within range of each other, they exchange these bundles. The goal of such a scheme is to introduce high reliability, short latency, and low storage cost. Such an approach can be implemented on a multinetwork topology. Links or nodes of different network access network topologies and their interactions. This is a multilevel approach to organize networks based on connectivity features and node stability.

3.5 Cognitive Radio-Based Communication over Cyber-Physical Systems

The Internet of Things (IoT) has ushered an era of connected devices. Starting from personal appliances and gadgets to the large-scale industrial applications, many devices are kept connected while fulfilling single to multi-objective tasks. Cyber-physical systems usually remain connected over wireless medium. Since multiple devices are in the play, the idea of efficient wireless channel utilization and energy efficiency over radio transmission are challenging. Hence, cognitive radio-based communication may be a solution to enhance efficient wireless channel utilization. Therefore, it can achieve energy efficiency and load balancing in CPS.

3.5.1 Cognitive Radio-Based Communication

The emergence of cognitive radio is from the idea of efficiently utilizing the radio electromagnetic spectrum. *Cognitive radio* is a software-defined radio built as an intelligent wireless communication system which learns from the environment and adapts to the changes in the wireless medium. This is a popular technology because of a couple of reasons [89–92]. Firstly, some frequency bands are partially utilized while some other bands are unused and unoccupied for the most of the time in wireless communication. Secondly, a part of the bands are more frequently utilized. Consequently, it is necessary to utilize the available spectrum judiciously, where unused and available spectrum are allocated to another user which is currently in need. According to [93], the primary objectives of cognitive radio can be summarized as follows:

- Communication with high reliability
- The efficient utilization of channels or radio spectrum.

We can see the basic steps of cognitive radio cycle in Fig. 3.19. Cognitive radio is a reality today. It is a combined effort of digital radio and computer software [94, 95]. Implementation of cognitive radio is based on some pre-defined tasks where signal processing techniques and machine learning tricks are being used. The study in [93] stresses upon three cognitive tasks—*radio scene analysis, transmitter power control and spectrum management, and channel-state estimation and modeling*. Figure 3.19 shows the steps. Here, the first and third tasks are carried by the receiver, while the second task is managed by the transmitter. The radio environment makes this interaction possible, and together they bind together and form a cognitive cycle [93]. Despite having a holistic overview of how cognition works in radio environment, it is nevertheless the task of the designer to employ the degree of cognition in cognitive radio-based communications. For example, the designer may pick a fixed spectrum for communication and adapt this cognitive cycle to that spectrum. Hence, both transmitter and receiver judiciously use the fixed

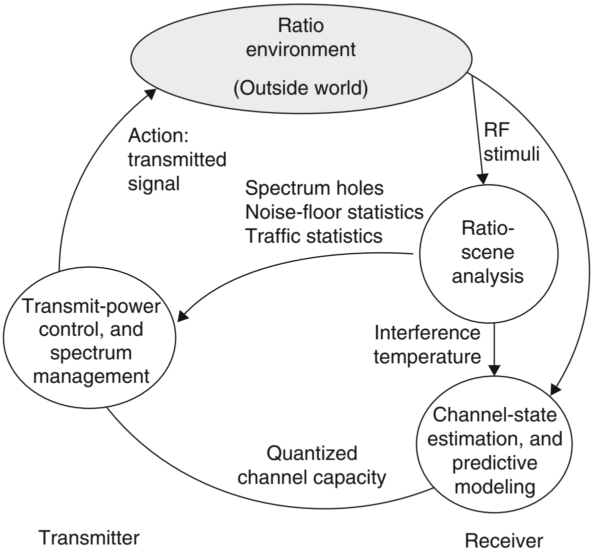


Fig. 3.19 Basic cognitive radio processes [93]

radio spectrum. It also designs this cognitive cycle across multiple band spectrum and reaches a target optimum that matches this designed performance and meets the expectations.

Pertaining to a macroscopic point of view of cognitive radio, there are two broader sets of cyber-physical systems. Firstly, *vehicular cyber-physical systems*. Secondly, *industrial cyber-physical systems*.

3.5.2 Cognitive Radio-Based Communication over Vehicular Cyber-Physical Systems

Vehicular cyber-physical systems belong to CPS. Here, vehicular and road networks are physical systems and computing and communication can be called cyber systems [96]. Vehicular cyber-physical systems have been emerged with different applications, such as road safety, green transportation, artificial intelligence assisted driving, and self-driving or automated driving. Figure 3.20 shows interaction of different components that is a part of vehicular cyber-physical systems.

Challenges Vehicular cyber-physical systems come with some problems and challenges [96]. Topology of vehicular networks changes constantly based on vehicular speed and mobility. Therefore, vehicles may need adaptive transmission power over wireless medium to establish reliable connectivity. The 5.9 GHz IEEE 802.11p Standard has been dedicated for vehicular communications. It has seven channels. These channels could be over-crowded in the presence of high density vehicular networks. A number of studies have also shown that the statically allocated wireless

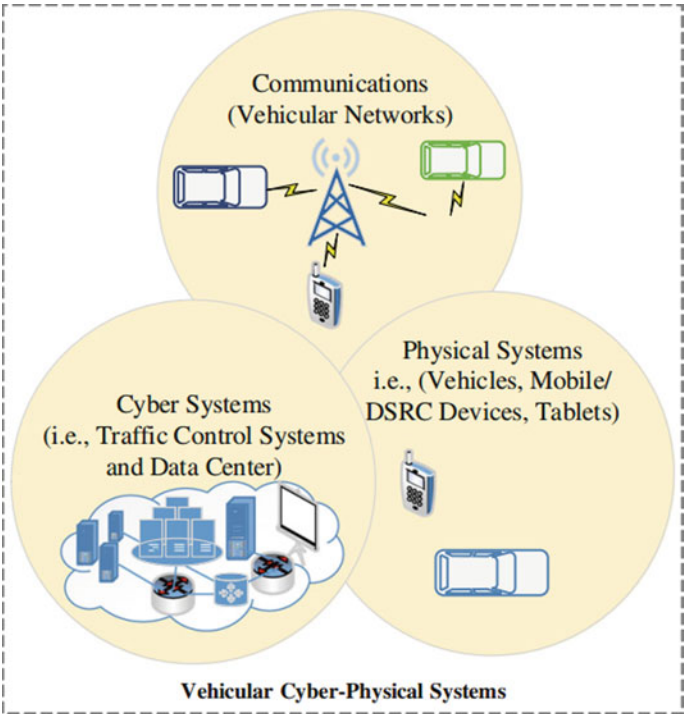
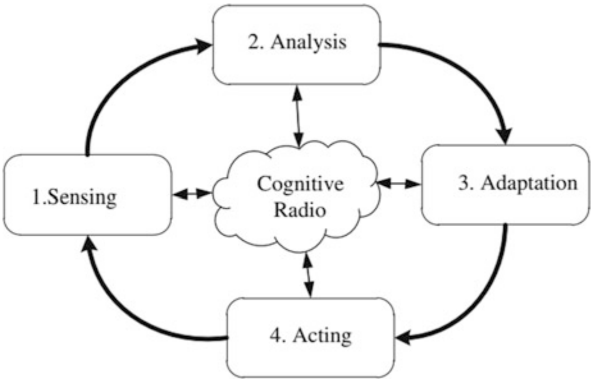


Fig. 3.20 Interaction of different system components in vehicular CPS [96]

Fig. 3.21 Cognitive cycle for vehicular cyber-physical systems [96]



channels remain underutilized or idle most of the time. Moreover, the vehicular ad hoc network is susceptible to high dynamic and frequent changes of network topology. The high mobility of vehicles gives rise to several challenges also. As a result, vehicles need to adapt to network and communication parameters on the fly (Fig. 3.21).

The main idea of cognitive radio is to make efficient use of underutilized spectrum bands. There are two categories of users involved in this case.

- *The primary users (PUs)* are those users having a licensed spectrum band for use (such as network operators in cellular networks).
- *The secondary users (SUs)* are those users who are unlicensed.

However, they can use the spectrum provided that the PUs are absent and not using the spectrum (such as vehicular users in cellular band) [96]. The unlicensed SUs access idle channels opportunistically. This is done through sensing, analysis, and adaptation in cognitive radio cycle. As a result, any harmful interference to the PUs is avoided [96].

Transportation Cyber-Physical Systems There is an array of research that targeted spectrum access in cognitive radio networks. A similar track to vehicular cyber-physical systems is called *transportation cyber-physical systems*. Owing to high density of vehicles at any time, the IEEE 802.11p-based communication suffers from delay and unreliable communication. The study in [97] presents a solution to this problem. In order to provide a reliable communication, they assume that one transceiver will always query spectrum database for connectivity by remaining connected to internet, and the other transceiver will switch channels to adapt transmit parameters. Thus, there will not be any interference with PUs.

Figure 3.22 shows a system model diagram that is considered in [97]. The underlying architecture supports a distributed cloud-based system. The assumption is that, as soon as a vehicle starts for a destination, one of the transceivers (or GPS) suggests the best route to the destination. At the same time, this transceiver calculates the spectrum opportunities along the route towards destination, and also recommends for use en route. Since the vehicle itself is a SU cognitive radio, it periodically searches for spectrum opportunities in order to avoid interference with PU. For example, in Fig. 3.22, when the vehicle enters the road segment S2, it cannot use Wi-Fi channels 1 and 6 because residential Wi-Fi users (considered as PUs) are using them.

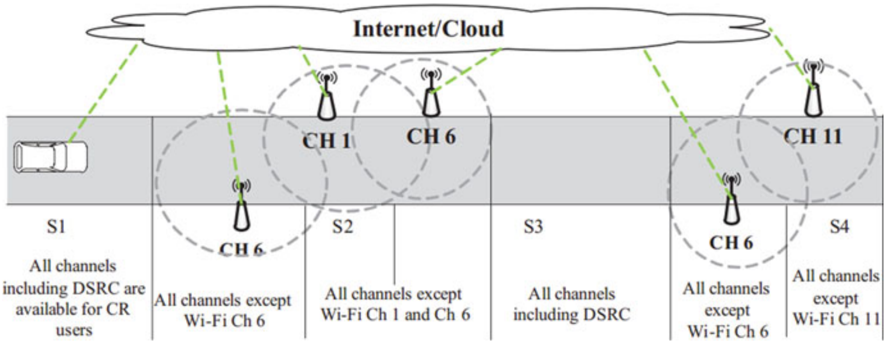


Fig. 3.22 System model for [97] where road-side Wi-Fi users are PUs

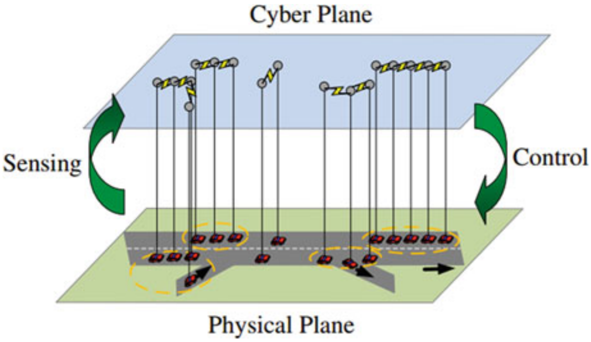


Fig. 3.23 Illustration of platoon-based vehicular cyber-physical systems [101]

Impact for Mobility Reducing loss of data or communication during spectrum mobility is an important research problem. Since the main tasks of cognitive radio are spectrum sensing, management, mobility, and sharing [98]. Therefore, cognitive radio is expected to solve spectrum mobility problems [99]. The work in [100] introduces a fear inspired spectrum mobility scheme. Based on a survey on different GSM service providers, a probabilistic deterministic finite automaton can be proposed. The idea is to use fuzzy logic to represent different emotion states. These emotion states quantitatively represent different communication parameters and resemble the need for spectrum handoff (Fig. 3.23).

3.5.2.1 Clustered Vehicular Cyber-Physical System

While most of the work related to vehicular cyber-physical systems are based on individual vehicles, some other work has opened a new paradigm of *clustered* or *platoon-based* vehicular cyber-physical systems. In order to tackle issues related to traffic congestion, mobility, and traffic dynamics, platoon-based driving pattern has been suggested as a viable approach [102]. Platoon-based driving pattern has several benefits. For example, vehicles in the same platoon will remain closer and avoid congestion, streamlining vehicles one after another in a platoon will reduce drag and thereby save energy consumption, and relatively fixed position among the vehicles allows them to share data and communication channel and thereby improves vehicular networking [103]. In order to support platoon-based cyber-physical systems, two issues are involved:

- Issues related to vehicular networking and architecture
- Vehicle mobility models and traffic flow distribution.

[101]. The work done in [104] discusses about specific issues with vehicular mobility and handoff management. The challenges of vehicular communication caused by high mobility and there some suggested solutions for host-based applications.

3.5.2.2 Maritime Cyber-Physical Systems

Limited spectrum opportunities, long distance communications, obstructions due to high density sea clutters and vessels, etc., are some of the problems of radio communication in maritime cyber-physical systems. Yang et al. [81] proposed a cognitive cooperative framework for providing opportunistic spectrum channel access in the sea. In this framework, SUs utilize the full transmission power for a specific period of time as a reward due to cooperation with PUs. Under this framework, each entity in the sea (for example, vessel, sea farm, oil/gas platform, etc.) should be equipped with sensing and communication devices. While registered or licensed users (or PUs) have spectrum opportunities, this framework makes opportunities for secondary users or unlicensed users to transmit messages on licensed spectrum. The framework proposed a game-theory-based resource allocation strategy which has been implemented in the MAC layer.

3.5.3 Cognitive Radio-Based Communication over Industrial Cyber-Physical Systems

Industrial cyber-physical systems are integrated systems that utilize computation power to control, influence, and interconnect physical systems. By the term physical systems, we abstract any physical body having mass and occupy a space around us. Consequently, in broader perspective, industrial cyber-physical systems mean the interaction between machine to machine and any other physical processes over cyber networks.

A broader range of research problems has been discussed in literature concerning industrial cyber-physical systems and cognitive radio networks. The most common topics concerning these domains are resource management in cognitive radio network, quality of service, state estimation, channel estimation, etc.

Resource Allocation The literature in [105] offers a comprehensive discussion on resource allocation problems in cognitive radio networks. This work has presented a systematic study on different design approaches such as signal-to-interference-noise-ratio, centralized or distributed framework based, etc. The work has also covered spectrum allocation and resource sharing options, in particular spectrum aggregation and frequency mobility. The work in [106] discusses about resource allocation problems based on some criteria, for example, interference, power, fairness, delay, topology nature—centralized or distributed, etc. Compared to this work, [105] provides basic mathematical formulation for resource allocation problems. They also discuss about the quality of service problems in relation to resource allocation problem. The literature in [107] discusses about cognitive radio network architecture on resource allocation. Their work is primarily based on efficient spectrum sensing and detection procedure in order to make proper resource allocation. The work in [81] considers resource allocation problems in maritime network topology and developed an opportunistic channel access framework for SUs over PUs.

The work in [108] discusses a multi-objective framework for resource allocation in cognitive radio network. Their design approach considers minimizing total transmit power, efficiency in energy harvesting, and minimizing interference power leakage-to-transmit power ratio. Their study revealed some interesting observations. For example, while allocating resources, the policy of minimizing total transmit power leads to low interference power leakage in general. Moreover, it has been found that energy harvesting maximization conflicts with the objective of minimizing transmit power.

Industrial cyber-physical systems often depend on sensor output to optimize industrial flow controls and control actuators and other peripheral systems. State estimation is the process of ensuring real-time monitoring of industrial processes and actions. Therefore, it is very important that sensor data reaches through wireless medium to the control node for further actions. This is a vital step for controlling system performance in industrial cyber-physical systems using integrated techniques of control and communication. As a result, much of the success of state estimation depends on reliable communication through wireless medium. In industrial wireless techniques, redundant channels are thus reserved to ensure reliability of wireless communication. However, introducing redundancy burdens the over-crowded ISM band. Cognitive radio communication has been emerged as one of the solutions to such problems. Cognitive radio can intelligently sense available spectrum and let SUs use unutilized spectrum from PUs. Different array of research methodologies have been adopted in this regard. The work in [109] proposed a cognitive radio enabled energy-efficiency maximization problem for state estimation convergence with the constraints of resource allocation. The given problem is a non-convex problem. They adopted a couple of relaxation techniques to transform the problem from non-convex problem to a convex problem. The work in [110] takes a different approach by modeling a channel sensing and switching mechanism called CHANCE. Their algorithm and process depends on channel quality and sensing accuracy, and took an iterative design approach by at first establishing a working technique for a single licensed and unlicensed channel. Then they extended their technique for multi-channel scenario. While state-of-the-art techniques rely heavily on network throughput, the work in [110] argues about considering communication reliability and state estimation performance as important variables. Nevertheless, a different category of research work considers two important parameters related to spectrum sensing—probability of detecting an unutilized spectrum and probability of false alarm generated by SU [111]. When the probability of spectrum detection is higher, PUs are protected since interference will be less to none. From the perspective of SUs, their objective is to lower the probability of false alarm generation. This in turn improves channel re-utilization and efficiency. The bottom line is that SUs always try to maximize their network throughput. The work in [111] mathematically formulates the sensing-throughput trade-off. Their work has revealed that an optimal sensing time can significantly improve throughput in SU. Finally, a recent trend in research has started focusing on blending of cognitive radios with multi-radio technologies in road to enhancing the performance metrics [112]. The studies suggest that such blending may not necessarily improve all the metrics.

3.6 Cloud-Connected Cyber-Physical Systems

In earlier days, classification of computing systems consisted of mainly two categories—traditional mainframe and desktop computers, and computing systems for controlling physical devices. Unlike the pasts, today's systems are interconnected. In other words, the physical and human systems are now connected through what we call to be a cyber space. Today, almost everyone has a desktop or laptop computer. Millions are the users of smartphones. These smartphones and laptops are now connected and synchronized. Surveillance systems today update video footage and camera positions instantly in real-time. From motion-aware systems such as airplanes or road vehicles to systems under ocean, there are constant interactions between physical systems, humans, and the cyber space. Combined together, there is a vast network of computing power and resources in sensors, actuators, and other networking devices. Such state of interconnected devices often requires scalability in terms of users and processing powers. Cloud architecture evolved to meet such needs, delivering computing powers and processors whenever needed. As such, systems and devices are continually appearing to us as ubiquitous and pervasive through exploiting cloud computing architectures.

3.6.1 Cloud Computing

Cloud computing and cloud services appeared to have a lasting impact in the ICT industry. The US National Institute of Standard and Technology upholds some key elements of cloud computing while defining cloud computing as follows [113]:

> Cloud computing is a model for enabling convenient, on demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.

Over the time, several important service paradigms of cloud services evolved. Nowadays, there exist three prominent service models that collectively refer to cloud services [114]. The service models are

1. Software as a service (SaaS): Clouds offer software support to consumers. Cloud service providers or application developers release their software suit and deploy in the cloud to achieve scalability, speed, security, availability, and other resource optimizations. Consumers extract benefits of the cloud-powered applications

through abstraction models developed and provided by the service provider. Some examples of SaaS are email services (Yahoo mail, Gmail, Outlook, etc.), Google Docs, Overleaf, etc.
2. Platform as a service (PaaS): Clouds offer platforms to support the entire life cycle of software and services. Here, customers or developers can associate the entire development and deployment life cycle of their services with the cloud platform. Consequently, developers need not have to shift their development environment while prototyping their deployment cycle. Some popular PaaS are Amazon EC2, Google AppEngine, Microsoft Azure, etc.
3. Infrastructure as a service (IaaS): Clouds provide an abstraction to the consumer or developer of a huge computing resource under the hood. IaaS providers share access to virtually infinite amount of resources, such as devices, processing units, and storages. Virtualization is an important part of IaaS. The underlying idea is to set up virtual machines that are independent from the hardware and other similar virtual machines. Popular examples of IaaS are Amazon AWS, Microsoft Azure, IBM SmartCloud Enterprise, etc.

It is evident from the examples presented in SaaS, PaaS, and IaaS that cloud computing has surpassed a long path from sharing multi-core resources to sharing virtual environments ranging over mainframe computers to tiny wrist-band watches. Within such domains, two important sub-domains are highly related to cyber-physical systems, namely vehicular systems and health monitoring systems.

3.6.2 Cloud-Connected Vehicular Cyber-Physical Systems

In Sect. 3.5.2, we discussed about how cognitive radio-based communication solves some of the problems inherent with vehicular cyber-physical systems. In this section, we restrict our discussion to cloud-connected vehicular models only.

Vehicular networking has been a well-established research problem [115]. In recent times, some novel applications evolved exploiting sensors and actuators that help in decision making and autonomous control of vehicles [116]. Essentially, the control of these two dimensions (vehicles and sensors) has given rise to vehicular cyber-physical systems (VCPS) [116, 117]. Until recently, the idea of mobile cloud computing has emerged with VCPS as a coherent solution to emerging networked VCPS problems.

Figure 3.24 shows a hierarchical model of VCPS [118]. Based on spatial regions, there are three different layers in VCPS. First, the micro layer is a combination of intelligent embedded systems, environment sense and control factors, and human factors. Second, the meso layer is mostly related to cluster-based vehicle movement including networked vehicle routing called VANET. Finally, the macro layer provides control, information, and all kinds of services to improve quality of service (QoS), network throughput, real-time traffic updates, etc., to the clients or customers.

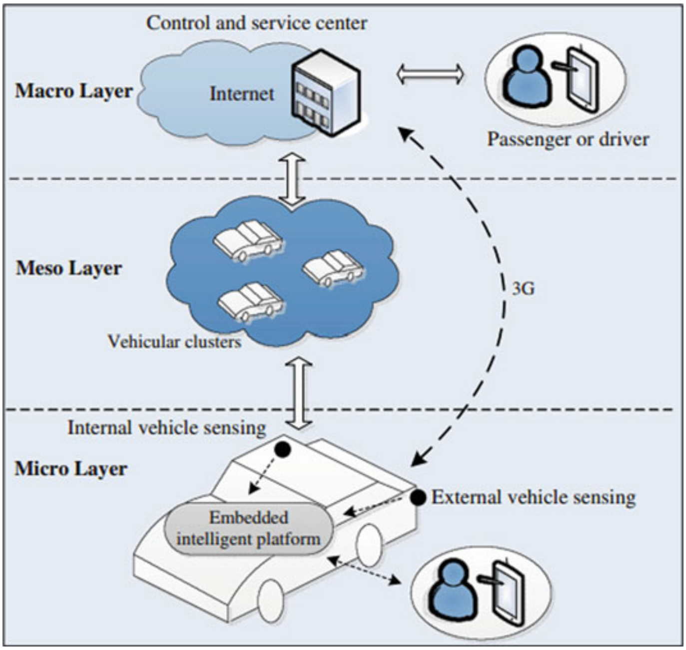


Fig. 3.24 Hierarchical model of VCPS [118]

The conceptual architecture of cloud-based VCPS [118] is primarily based on two basic ideas—first, mobile applications can be deployed to access larger and faster data storage centers for fast processing and information retrieval, and second, different mobile applications are developed based on differing architectural support to deliver cloud-based VCPS efficiently. In Fig. 3.25, the mobile devices take up the task of acting as a gateway to Internet connections outside the vehicle. A cloud server acts as a data storage and processing unit to take necessary decisions based on data gathered from several sensors and actuators in the vehicle through appropriate gateway mobile devices.

Contrary to explaining different architectural support, [119] takes on explaining state-of-the-art challenges on VCPS and cloud-connected support. Pertaining to existing VCPS problems with cloud-connectivity, the study in [119] explored the idea of context-aware cloud-connectivity where vehicular social networks and vehicular security have been explored. As a proof of concept, a context-aware dynamic car parking service has been proposed. To delineate on context-aware services, we can take some real-life scenarios as examples, such as real-time traffic live feed or availability of car parking facilities in a large shopping mall. The work in [120–122] provides some examples of context-aware traffic applications (Fig. 3.26).

Availability of parking services has been an intriguing problem among developed and developing nations. The usual scenario involves unavailability of parking spaces and parking-lot seekers wandering around for parking-lot availability. Some

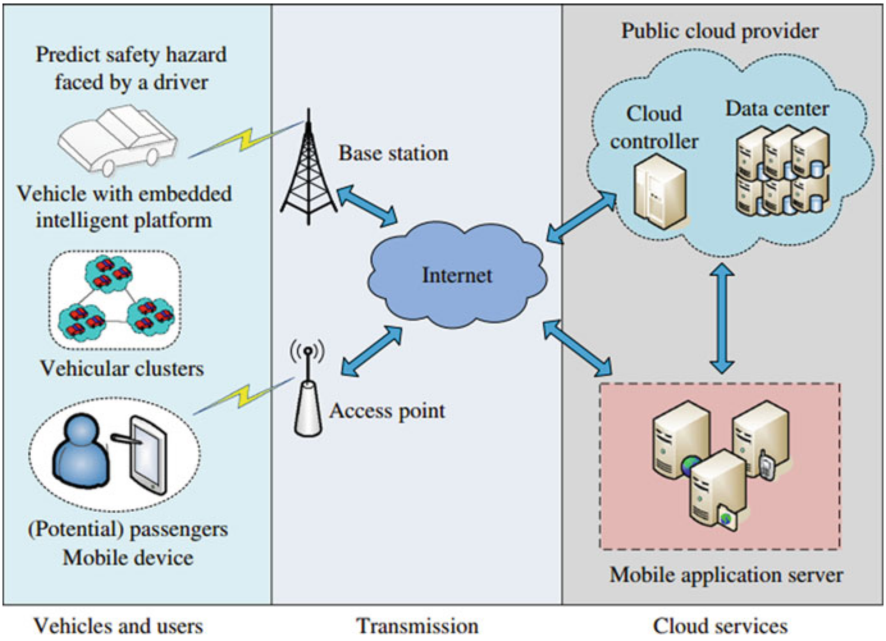


Fig. 3.25 Architectural model of cloud-based VCPS [118]

improved parking-lot facilities publish parking statuses over a billboard to inform incoming cars about possible parking spaces. Furthermore, a dynamic parking allocation scheme [119] may allow cars to park over a road temporarily, provided that it is not impeding any usual traffic movements. Contextually, the model employs road-traffic behavior. For example, it is well-known that traffic flow exceeds beyond capacity in some cities during rush hours such as morning and evening. Based on this contextual information, the system can update parking allocation schemes on wider and narrow roads, busy and non-busy roads, etc., accordingly. Moreover, in order to improve dynamicity, potentially empty parking lots are also considered within a window of specific time intervals. For example, the system can query a driver about his/her expected time of stay and departure from the parking facility. In this way, whoever is willing to park in the next few hours may consider parking in the same lot by observing potential empty time slots in future. As a result, context-aware optimizations may help improve traffic situations in countries where parking spaces are scarce.

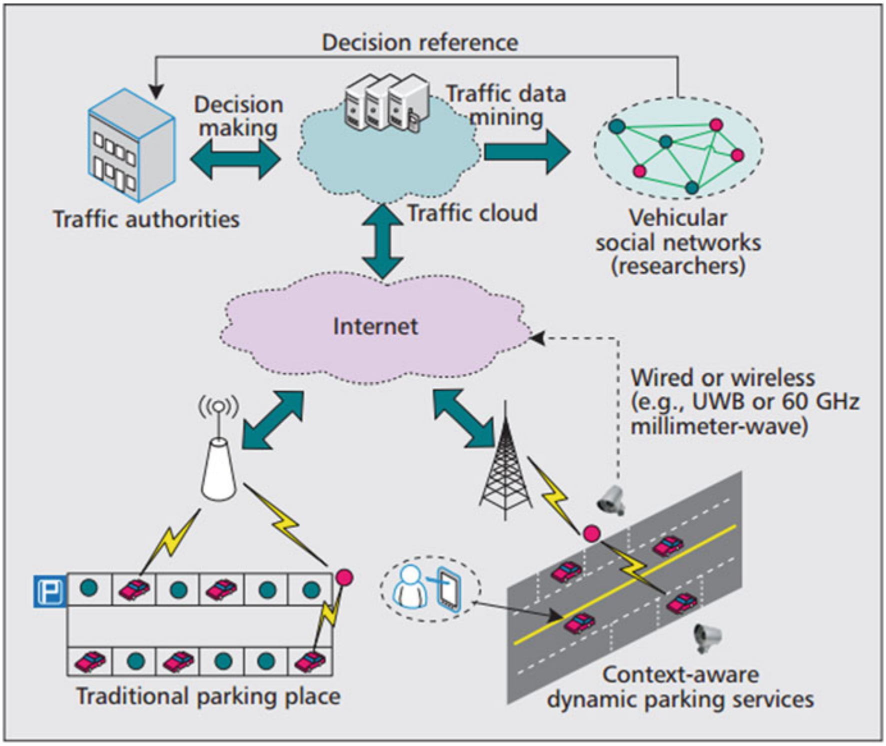


Fig. 3.26 Context-aware dynamic parking services [119]

3.6.3 Cloud-Connected Cyber-Physical Systems in Health Monitoring

Cloud-connected cyber-physical systems (CCPSs) combine the power of networked communication and computation with physical devices. Portability of such smart mobile devices, networking capabilities, and localization technologies has made CCPSs deliver promising tools for health care and monitoring [123]. One of the most popular mobile devices in this regard is the smartphones. Smartphones possess necessary computation power, multi-radio networking capabilities including GSM, Wi-Fi, Bluetooth, etc., localization capabilities utilizing GPS and other indoor-localization mechanisms based on Wi-Fi, inertial sensors, etc. [124]. Through off-loading complex computational steps, mobile CCPSs have opened an important field of research for patient monitoring, patient localization, and the health care services.

Existing studies based on CCPSs focus on quality of service (QoS), services related to general to specific illnesses, services provided to the elderlies, monitoring and localizing patients, etc. For example, several modern applications and devices have been developed to monitor different human vital signs [125]. Here, an array of devices generate huge amount of data at each period of time. Modern devices take help of cloud-powered applications to abstract and off-load huge computation required on the data from the data collecting devices to remote devices [126]. Thus, quality of service (QoS) becomes an important area of consideration for researchers and industries to ensure quality of data and quality of medical interventions in case of such off-loading. The area of research in this case often covers the trade-off among real-time collection and processing of data, prompt and swift health monitoring, dispatching timely medical interventions, quality of data sampling, etc.

Several key players [126] play important roles in this ecosystem. First, the physical aspect or the devices that measure and monitor data, second, the infrastructure that backs up this physical devices, for example, network architecture, processing and computing power, etc., and third, data analysis and management from the gathered data. Assuring quality of service among the three is a hard problem. Since health monitoring is a sensitive issue, it demands that the devices should offer near to 100% accuracy while accumulating data. While in some cases, these data are used for real-time analysis; however, in most cases, these data are used as a backbone machine learning analysis data to ensure future data are predicted with better accuracy. As a result, power consumption at device level shoots up considering the requirement of fine-grained sampling of personal health data. Increasing power consumption arrive at a price—for example, the fit bands that are available in our local market may consume more power if we want fine-grained sampling and monitoring of our health data. While ensuring data fidelity is desirable, it is equally less desirable to consume huge power in data collection only. Moreover, we know that, the more data that we collect for analysis, the better will be the outcome of the analysis. To ensure quantity of data, network infrastructure has to do a better job. However, networked components such as Wi-Fi, GSM, and Bluetooth consume data while transmitting data to the cloud. Consequently, data throttling rate has to reach an optimum where the trade-off between data quality and energy consumption in networked architecture is a research issue.

A recent trend of research is directed towards amalgamation of smart textile clothing and CCPS. The work in [127] introduces Wearable 2.0 for efficient health monitoring by exploiting human–cloud interaction. The idea is to ensure quality of experience (QoE) and QoS in smart clothing and advanced cloud services to deliver a reliable service to the customers. Here, they proposed a washable smart clothing. This smart clothing consists of sensors that continuously monitor health informatics data or human vital signs and then send these data to the analysis machine in the cloud. The proposed system harnesses the infinite power of cloud-based machines in analysis part. Figure 3.27 shows extension of the proposed idea to other domains where monitoring of human vital signs is essential.

Unlike the work in [127] where a generalized solution is provided, the work in [128] specifically engages elderly people in its design process. In this work, the authors monitored and observed how elderly people operate smart applications and appliances. In this aspect, the idea of energy consumption and energy efficiency has been explored. Elderly people often face difficulties in navigation and swift

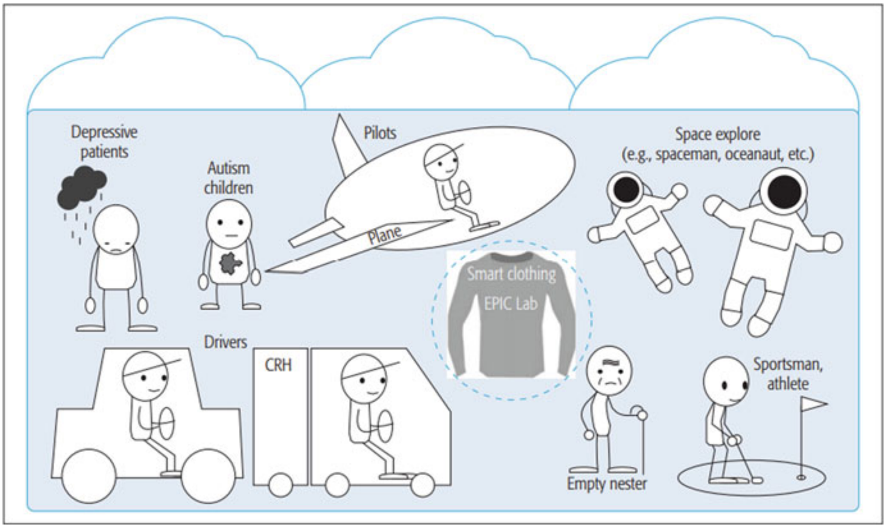


Fig. 3.27 Extending Wearable 2.0 to the cause of special groups of people and applications [127]

operation of electrical appliances. For example, elderly people may often fail to switch on/off electrical appliances. A cloud-based activity monitoring approach has been proposed in [128]. In this work, user's gesture or voice-based input is recognized to efficiently perform regular activities by the elderly people. Since high dimensional input is fed to the system, it is imperative that such input modalities are less likely to be processed by local processing units or embedded system units. As a result, a cloud-based approach is highly likely to suffice in this architecture.

3.7 Conclusion and Future Work

3.7.1 Future Work

There are still many research challenges involved in the cyber-physical systems communication. The following could be potential future research issues:

3.7.2 MAC Layer

- Self-configurable Mac protocols can be customized based on application requirements, traffic loads, and the environment.
- For collision free connection, simple Mac layer without RTS, CTS can be used for energy efficiency. When collision is detected, mac layer protocol with RTS,

CTS can be utilized. Mac layer protocols can be tuned with the link quality and capacity. Hybrid mac layer (SMAC, Mac 802.15.4, mac 802.11), Qos-aware Mac can be modified.

3.7.3 Network Layer

- Network layer considers platform heterogeneity (heterogeneity among sensors, actuators, and controllers).
- Routing protocols design affects the performance of CPS (considering energy efficiency, resource constraints, low latency, high throughput, low packet drop, low energy per bit, link quality, and path existence).
- Tree-based, cluster-based routing, and dynamic routing depend on the application requirement and architecture of CPS. Existing WSN routing protocols can be modified for CPS requirements also.

3.7.4 Transport Layer

- Dynamic congestion control mechanism can be explored based on the system architecture, packet drop, and window size. Optimal window size can be designed based on the requirements of CPS (i.e., traffic loads)
- Round trip time: Round trip time based on network performance (low packet drop, high packet delivery) can be tuned based on each subsystem of CPS. Existing UDP and TCP with specialized mechanism of RTT can be designed based on data importance, traffic load, network scale, and network behavior.

3.7.5 Multi-Channel Assignment

- Optimal multi-radio multi-channel assignment can be explored for each device in the CPS (based on connectivity, data importance, data flow, network topology, traffic load, and physical environment).
- Applications of existing WSN channel assignment techniques can be mapped for CPS based on system architecture and requirements.
- Power and resource management are most important issues for multi-radio multi-channel assignment. Optimal channel assignment minimizing these two metrics should be studied for different types of CPS applications.
- Multi-radio multi-channel assignment to minimize interference for different types of CPS applications (transportation system, health care system, and environmental monitoring).

- Channel assignment based on different metrics of different layer (cross-layer design) should be studied for CPS.

3.7.6 Mobile CPS

- There are many challenges involved in vertical and horizontal handover protocols for mobile nodes of CPS while communicating with a base station.
- Design automation of electric vehicles—electric vehicles are next generation vehicles that are power and battery charge critical. Electric vehicles may potentially face charging problems in regions where traffic mobility is slow and congested. For example, developing countries like Bangladesh, India, where energy constraints exist, induction charging or the energy harvesting mechanism for CPS can be explored.

3.7.7 Cognitive CPS

- Multi-objective optimization for cognitive radio used in CPS is a challenging issue.
- Transmit power minimization and energy harvesting efficiency maximization are conflicting design objectives in CPS.

3.7.8 Cloud CPS

- For complex industrial applications, different clients maneuver cloud-based CPS are being used based on their needs. A common framework for basic design goals and a prototype based on those design goals are yet to be established.
- Cloud-connected CPS, exchange information between different devices. This information exchange mechanism needs to be formalized based upon a common framework or protocol.
- Big data-based cloud CPS optimization is needed in terms of energy consumption, data fidelity, QoS, etc.
- Historical manufacturing process and performance can be integrated and maintained in a cloud-based knowledge repository. Combined with intelligent controllers, the future manufacturing processes can be improved continuously and design must be mapped for CPS.

CPS communication introduces many research areas, and the generated big volume of data has made this research area colorful and interesting.

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