Collision Avoidance Systems for Underground Mines

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With the growing number of unintentional interactions occurring in underground mines, Collision Avoidance System (CAS) establishment and maintenance has become an urgent need for mining industries to enhance their risk profile and improve construction safety.

collision avoidance underground mine positioning techniques

1. Introduction

The rapid development of mining, especially in underground mining, is driven by the ever-growing demand for mineral resources. There are numerous potential hazards and risks in underground mines. Therefore, a plethora of techniques have been developed and deployed to protect mine workers from risks. Most risks arise as a result of mining workers being in the vicinity of vehicles and vehicles operating in constrained environments: vehicles and personnel (V2P), interactions between vehicles (V2V), and vehicles and mine infrastructure (V2I) [1][2]. Of these, the highest risks are collisions between vehicles and vehicles and personnel [2][3]. In order to minimise these risks, it is necessary to improve situational awareness for mine workers and vehicles by developing automated collision detection systems [4]. The challenge is to provide a Collision Avoidance System (CAS) design that can effectively and accurately take action in confined harsh environments with poor visibility, such as those in underground mines.

In general, a CAS consists of three subsystems that need to work together seamlessly, namely subsystems for proximity detection, decision making and intervention control, as shown in **Figure 1**. The performance of proximity detection relies on sensors to detect objects. The sensors can be visual (e.g., video cameras), ultrasonic, acoustic or electromagnetic (e.g., radar). Actually, proximity detection can be referred to as obstacle recognition as well. If any vehicle/infrastructure in the vicinity can be inspected in advance, and the warning signals can be sent out accordingly, the successful rate of collision avoidance can be improved, and the false alarm problems can be also alleviated [5][6]. Decision-making subsystems consolidate the information obtained from the proximity detection subsystem to determine whether there is an imminent hazard. If there is, it informs the intervention control subsystem to take the necessary actions to avoid the hazard.

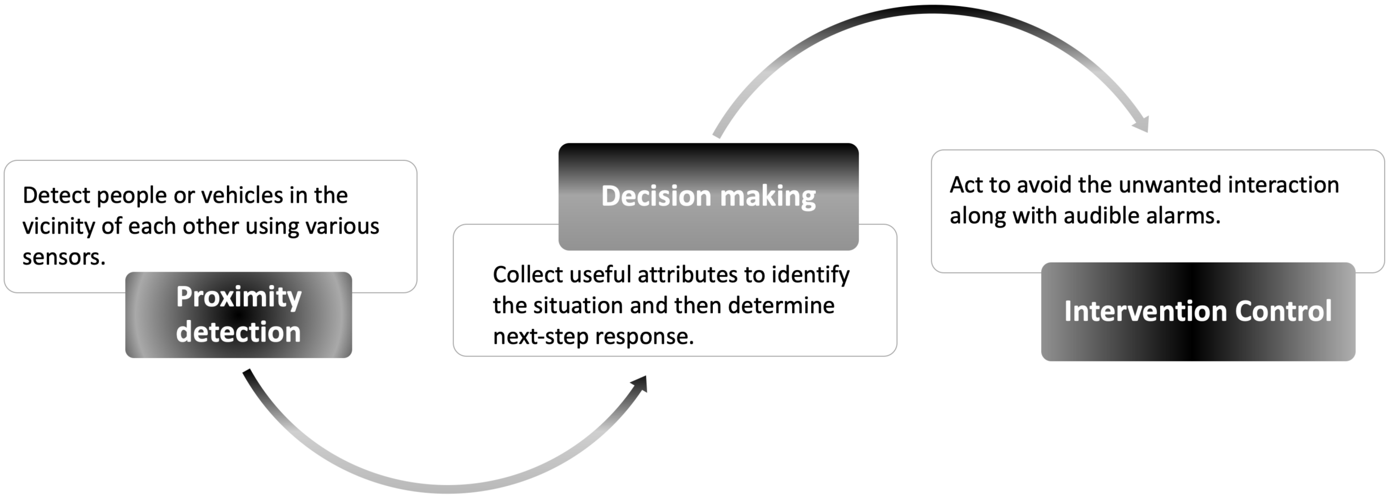

Figure 1. The working flow diagram of a typical CAS.

The decision-making part is mainly related to the logical judgements and making a final decision based on the instant situation. According to the result of the proximity detection subsystem, it determines whether and how to react. The design of intervention control depends on specific application scenarios and/or the requirements of the local service providers. It is usually composed of audible alarms and vehicle interventions, such as applying the brakes or steering away from the hazard.

2. Medium Access Control Methods and Communication Protocols

2.1. Desired MAC Protocol Design for CAS

In terms of a successful CAS design, proximity detection based on different detection capabilities is required. Correspondingly, a suitable communication system is also important, which is used to arrange multiple sensor nodes to perform proximity detection in order. A complete communication system needs to have advanced communication technology that is suitable for low-power and long-range networks (i.e., LPWAN). The system also relies on an appropriate MAC protocol to share the common communication channel without packet collisions and exchange information with each other with minimum latency.

The frequency channels occupied by the signals used in the proximity detection systems and the communication systems need to be separated to avoid mutual interference. This can be achieved using three techniques, namely Frequency-Division Multiple Access (FDMA), Code-Division Multiple Access (CDMA), or Time-Division Multiple Access (TDMA). In the CAS design for underground mines, the channel access opportunity for each node has to be scheduled in advance in order to avoid packet collisions. Therefore, FDMA and CDMA are not suitable for underground applications in most cases due to the limited bandwidth that can be provided in the underground mining environment [7][8]. Additionally, CDMA relies on complex modulation, which increases the difficulty of implementation [9][10]. As a result, TDMA, using fixed assignment of time slots, offers the highest probability to be implemented in underground applications [11][12].

In order to create and maintain a contention-free communication channel, TDMA provides a way of time slot distribution for all devices in the neighbourhood. In order to have an organised time schedule without any packet collision, it is necessary to consider the following features and requirements for a desired medium access control method.

2.1.1. Distributed Networks

In terms of a ranging-based proximity detection systems, multiple devices need to interact with each other and use peer-to-peer connection. Particularly, when using the TOF strategy to perform two-way ranging, a star network topology would be preferred if vehicles/personnel are close to each other. In such a setting, the ranging request will be initiated by a master node and received by the rest of the nodes individually.

2.1.2. Contention-Free Communication

The communication between the devices needs to be reliable and efficient regardless of the number of the involved vehicles/personnel. In addition, each round of ranging process has to be completed without any interruption. This requires that the transmission of ranging signals needs to be collision free.

2.1.3. Scheduling Protocols

In an underground mine with moving vehicles and mine workers, a flexible scheduling mechanism that assigns each time slot to the appropriate device is required. Furthermore, the system needs to accommodate numerous application scenarios including both long straight tunnels and confined corners, regardless of the size of the coverage area. In addition, several critical parameters need to be taken into consideration, such as the maximum time delay, network capacity and energy efficiency.

2.1.4. Latency

One of the most important features of a CAS system is latency. Latency depends on the time delay used to contend for channel access and the time taken for message delivery.

2.1.5. Energy Consumption

In order to have a successful CAS design for underground mines, a multitude of proximity detection sensors and communication devices are necessarily deployed over a vast area. Due to the hostile environments and limited power supply in the underground mines, energy consumption is normally the first priority to be considered in order to keep the network composed of various devices working over a relatively long period with no need for regular maintenance or battery exchange. Although, if all devices are mounted on either vehicles/machinery or personnel rather than fixed infrastructure, the problem of limited power supply can be resolved easily without extra effort. In that case, energy consumption would be viewed as a second important factor only to over latency. In fact, energy efficiency as a critical evaluation metric among abundant available MAC protocols also has an interactive relationship with end-to-end delay, packet delivery reliability and channel maximum throughput. Based on a thorough understanding of power dissipation in different MAC protocols, there are three causes, namely overhearing, overhead and duty-cycling, to be further discussed below.

Overhearing

During the packet delivery phase, a node may hear signals frequently from the sender in the neighbourhood, whereas it is not the destination of the forwarded data packets. Even though idle listening without further process consumes less power than the intended node, the energy waste cannot be ignored since the sleep state of the same node saves much more energy than the idle listening mode.

Overhead

A sequence of control packets such as RTS and CTS may contribute to large overheads that consume a considerable portion of energy, which decreases energy efficiency significantly. Alternatively, various preambles, including short and long preambles, increase power consumption to a great extent. Particularly, long preambles do not convey useful information but occupy the limited resource of applications.

Duty-Cycling

In essence, the radio of sleep period and wake-up period determines the duty-cycle of MAC protocols. A sensible duty-cycling is capable of maximum energy efficiency and minimum end-to-end delay. A short duration of sleep period leads to intense power consumption, whereas a too long sleep scheduling can potentially cause a large time delay to wait for the response from the next hop that is in sleep period.

2.1.6. Scalability

In terms of the application scenario in the underground mines, there might not be many vehicles and personnel in the proximity. However, in other complicated applications, such as an intelligent mobile app used to keep physical distance during the COVID-19 situation, there probably is a need to consider the network scalability when designing a suitable MAC protocol. In order to make the designed MAC protocol with enhanced adaptability and flexibility to accommodate different kinds of applications, the system scalability should be paid attention to appropriately.

2.1.7. Traffic Adaptability and Throughput

In terms of an effectual communication protocol, some other evaluation metrics are worth mentioning, though they are not critical factors to be considered for CAS design in underground mines. Traffic adaptability provides a potential way for a flexible time scheduling mechanism to further improve energy conservation and reduce time delay, respectively [13][14]. Additionally, channel throughput cannot be ignored as well. Based on limited frequency resources and a plethora of devices deployed in some applications, it is necessary to have an exceptional performance in system throughput via the employment of variable scheduling mechanism and minimised possibility of packet collisions [15].

2.1.8. Handling Mobility

The mobility awareness provided by MAC protocols specially caters to dynamic sensor networks. Adjusting resource allocation to ensure the fairness of distribution among all the deployed devices based on real-time mobile nodes is essentially important in CAS design, since most vehicles and personnel in the underground mine are usually in the non-stationary status. An accurate estimation of actual traffic flow and the number of involved nodes can provide the communication network with maximum channel efficiency and system capacity.

2.1.9. Wake-Up Radio Enabled

The communication system is designed to focus on time frame arrangement so that the proximity detection process can be conducted during corresponding time slots. Using external devices to reach different targets is also a useful algorithm when designing a suitable MAC protocol for communication systems. In other words, the deployment of extra wake-up devices on the side to assist the main communication device to have high sensitivity in time scheduling catering for dynamic wireless nodes.

2.2. Review of Existing Wireless Standards and MAC Protocols

In underground mine CASs, a large amount of wireless sensors are deployed, and the communications with these sensors over the shared communication channel need to be separated from each other. In other words, it is necessary to have a suitable medium access control (MAC) scheme, which will enable all involved distributed devices to be effectively managed.

2.2.1. Related Wireless Standards

The IEEE 802.11ah and IEEE 802.15.4 standards are capable of supporting efficient wireless long-range communication at low power consumption. The biggest difference between 802.11ah and 802.15.4 is the number of wireless devices that they can support [16].

IEEE 802.11ah

The IEEE 802.11 Working Group for wireless local area networks developed the first wireless standard, and that standard has evolved to support high-speed, wide coverage [17] and transmission technologies, especially Multiple Input Multiple Output (MIMO).

The latest standard, IEEE 802.11ah, supports low-power sensor network communication. It has also been adapted for long-range communication among a large number of end devices [16] using Relay APs. IEEE 802.11ah operates on the sub-1 GHz unlicensed frequency band to enable an extended operation range, and specially designed data structures are used to minimise the power consumption [18].

IEEE 802.15.4

WPANs are usually used to convey information privately over short distances among an intimate group of participant devices. They are dedicated to providing an effectual wireless communication approach within the personal operating space; a circular operation with a radius of 10 m centred on the primary device [19].

Typically, there are two types of WPANs, namely high-rate WPAN and low-rate WPAN. The IEEE 802.15.4 standard is particularly aimed for low-rate WPAN, and it provides corresponding lower-power physical and MAC-layer provisions. This standard contributes to the development of industry standards such as ZigBee and Bluetooth, which are mainly used for low data rate transmission at low power consumption. IEEE 802.15.4 uses the unlicensed 2.4 GHz frequency band and Direct-Sequence Spread Spectrum (DSSS) modulation scheme. DSSS employs a chipping code to “spread” the transmission over a wider frequency band than it would normally occupy [20]. In addition, the super-frame structure and sleep–wake strategy might be useful for this standard to improve energy efficiency.

2.2.2. Typical MAC Protocols

In order to have a high-performance CAS design for underground mines, a detailed table that reviews various MAC protocols is provided in Section 7. Moreover, a brief discussion of a few typical MAC protocols is given in different groups based on their different characteristics.

Latency

- **SR-MAC**

SR-MAC [21] is a synchronous MAC protocol with SYNC, DATA and SLEEP phases. Most of the existing medium access control (MAC) protocols for sensor systems are mainly optimised for the situation under which a device only generates one packet. As a result, when multiple packets are generated by a device, the performance of these MAC protocols degrades. SR-MAC overcomes this by using a three-phase operation: SYNC, DATA and SLEEP phases. It introduces a new scheduling mechanism that reserves few time slots during the SLEEP period to enable devices to transmit multiple packets, which allows the scheduling of multiple packets generated by a device to be transmitted in one operational cycle without collision.

SR-MAC uses a slot-reservation mechanism during the SLEEP phase of an operation cycle to schedule wake-up nodes to communicate. In the DATA phase, a device that wants to transmit data packets contends for the channel access using a CSMA/CA protocol. SR-MAC replaces RTS/CTS with a special control frame, called the slot-reserved frame (SRF). In the SLEEP period, according to the slot in which the node transmits the SRF, the neighbouring devices wake up to communicate with each other in the corresponding slot.

In the DATA phase, each pair of frame-based slots, and further-divided subslots in the third phase, are linked to a corresponding time slot in the second phase. The design of the Slot-Reserved Frame (SRF) instead of the Request-to-Send (RTS) and Clear-to-Send (CTS) frames, particularly for a receiver, enables not only the follow-up reservation deployment for itself but also a new reservation request for the next hop in the forwarding path. The enhanced scheduling mechanism provides multi-packet transmission over multiple nodes using cross-layer routing information to further decrease packet delivery delay. Additionally, in order to maintain energy conservation, the information of SRF is capable of informing only the involved nodes to wake up during the third phase and keep the rest of the irrelevant nodes with the least power consumption. However, the maximum number of packets to be transmitted in one operational cycle is limited and determined by the duration of frames and the number of subslots segmented within each frame.

- **SW-MAC**

Different from SR-MAC, SW-MAC [22] is an asynchronous low-latency MAC protocol with adaptive duty-cycle. The duration of wake-up and sleep periods is determined by real-time data rates or traffic congestion. In order to shorten the end-to-end time delay across multi-hop transmission, the employment of scout packets instead of long preambles facilitates the wake-up and sleep scheduling for corresponding nodes to be performed promptly. The scout-based scheme actually behaves as a triggering signal, which is similar to various preambles, and it solves the problem of large overheads by dividing them into small pieces, then encapsulating them into a series of wake-up packets. Furthermore, the Additive Increase/Multiplicative Decrease (AIMD) mechanism is utilised to adjust the duration of sleep state. It is extremely suitable for wireless network traffic with large variance by minimising the long waiting time caused by the next hop, since it is still in sleep period. In addition, SW-MAC has no stringent requirement for time synchronisation among a large number of nodes via alleviating the serious issue of heavy overheads occurring in the multi-hop forwarding process. The energy consumption is reduced impressively. The flexible duty cycle also provides energy conservation by adjusting the sleep-wake scheduling mechanism based on actual network traffic conditions. An important limitation of SW-MAC is the assumption of only one source node to generate packets for detected events that have been made upfront. In underground mines, there must be more than one vehicle with devices mounted inside working as the source nodes in actual application scenarios.

- **DW-MAC**

A synchronous duty-cycle MAC protocol providing low-latency capability based on considerable energy efficiency was proposed, called Demand Wakeup MAC (DW-MAC) [23]. It introduces a novel sleep–wake scheduling mechanism that allows nodes participating in the communication to convert between sleep and wake-up period on demand. DW-MAC has an exceptional performance when applied in congested networks with heavy traffic loads or large data rates due to its adjustable duty-cycle scheme. It makes use of the scheduling frame (SCH) to replace RTS/CTS and schedule nodes to wake up or fall asleep within each operational cycle. SCH works collaboratively with the designed mapping function to reserve corresponding time slots in the subsequent sleep period over the same duty cycle. The optimisation method using SCH for multi-hop packet delivery with reduced latency is typically dedicated for broadcast operation mode, although DW-MAC can be adjusted to be compatible with the unicast mode as well. Overall, the time delay reduction method mainly relies on the flexible sleep-wake scheduling mechanism, though DW-MAC enables significant energy conservation in addition to the relatively short time delay. The mapping function provided by SCH resolves the problem of hidden terminals so that conflict-free communication with reduced overheads is possible. However, the drawback of DW-MAC is obvious when compared with SR-MAC: there is only one packet that can be transmitted over each operational cycle, and multiple packet delivery is frequent to see in terms of event detection using wireless sensor devices. It has an essential impact on the final end-to-end delay and system capacity.

- **LDC-MAC**

The work of [24] presents a low-latency MAC protocol that is suitable for dual-channel communication networks. The time synchronisation over two independent transmission channels leads to extra energy consumption, which is a serious problem to be resolved. Meanwhile, the overall time delay could be potentially increased as well. Based on these facts, the design of the base station with no constraints in power supply was introduced in LDC-MAC [24] to schedule all the other nodes to deliver packets or keep idle listening from the perspective of global control. The duty-cycle of LDC-MAC that determines the duration of sleep and wake-up period can be adjusted for each sensor node according to the predefined packet forwarding path. Consequently, the latency is decreased because of the reduced waiting time caused by the sleeping state of the next receiver. The sleep–wake scheduling mechanism also has an impressive effect on energy conservation. Unfortunately, dual-channel communication systems are usually not available in underground mine devices. Most cost-effective communication devices that are suitable for underground mine environments have constrained resources either in frequency selection or channel bandwidth.

Energy Consumption Due to Overhearing

- **BBAD Mechanism**

In the wireless personal area networks with wake-up radio devices enabled, the validation process for the devices addresses was enhanced in [25] in order to resolve the overhearing issue and further improve energy conservation. The introduced method is based on a preset decoding scheme which process each address bit by bit with minimum possible error rate. The validation result based on the Bit-by-bit Address Decoding (BBAD) mechanism is reliable to avoid confusion, even when faced with abundant devices, but aims for only one node. The BBAD process is conducted within the intended receiver only, and it turns to sleep period automatically whenever one error bit occurs to save energy consumption.

- **RANO Mechanism**

An effective approach was proposed in [26] to inform each tag device of its time schedule, including active periods and inactive periods to improve energy efficiency via avoiding the overhearing problem. The Reservation Aloha for No Overhearing (RANO) mechanism can be implemented on each access point regardless of the network architecture (i.e., with or without a central node). The overhearing occurring on unintentional nodes can be resolved through a reservation and error recovery mechanism; the information for reservation and recovery is designed to be displayed by a particular byte representation to perform a comparison check. The RANO scheme works with a preset assumption that all involved nodes have been time synchronised accurately, which can be counted as a strict requirement. This protocol is designed for active Radio-Frequency Identification (RFID) tag devices and aims for energy waste caused by the overhearing problem. It implies an obvious advantage of significantly enhanced energy efficiency.

Energy Consumption Due to Overhead

- **LO-MAC**

The MAC protocol proposed in [27] is designed for wireless sensor networks with low data rates, and it provides a low-latency, low-overhead and energy-efficient medium access control method. The Pioneer (PION) packet is employed to replace the common control packet of RTS or CTS in order to mitigate overheads. The goal of PION packets is to initialise the connection among different nodes, and it actually includes cross-layer information that is useful for multi-hop transmission. The PION packet plays an important role in scheduling nodes to sleep or wake up separately using the nature of broadcasting to send control packets with different meanings. The LO-MAC [27] also makes use of duty-cycling and the optimised multi-hop routing algorithm to reduce latency. Additionally, an adaptive sleep–wake scheduling mechanism was incorporated with the Carrier Sense Multiple Access (CSMA)-based contention scheme to further improve energy efficiency and channel utility.

- **LoBigMAC**

In [28], a MAC protocol using the TDMA technique for data transmission and CSMA mechanism to contend for channel access was proposed. It provides a low-delay, reliable and power-efficient medium access control method using a receiver-initiated scheme to extend the network battery lifetime. A unique feature of this MAC protocol is its network architecture, which is a tree model. In order to construct a successful tree-shape network, time synchronisation has to be performed first. Then, a preset big shareable slot can be segmented and assigned to nodes on different levels in the tree model. Since only the nodes at the same level contend with each other to obtain channel allocation to send packets, differentiating nodes into various levels plays an essential role in reducing the number of control packets. Meanwhile, the structure of each divided big shareable slot is designed to minimise the packet collision rate. Consequently, the overhead effect is diminished, and power efficiency can be enhanced significantly.

- **LCO-MAC**

The LCO-MAC [29] is another typical protocol that focused on the overhead problem. It provides a reasonable solution for energy conservation based on the trade-off issues caused by the duty-cycling mechanism in most MAC protocols. To decrease the number of control packets, each packet is generated for multiple purposes that are different for uplink and downlink transmission. During the initialisation phase, the same control packet behaves as an RTS packet to be sent to the receiver node, whereas it acts as a CTS packet when transmitted to the sender node from the receiver end. Within the procedure of data transmission, the control packet with the same contents is capable of representing acknowledgements as well. However, it is only enabled in uplink transmission, but remains the original meaning during the downlink communication channel. In addition, it enables multi-hop transmission within each operational cycle to reduce packet delivery latency.

Energy Consumption Due to Duty-Cycling

- **BN-MAC**

The hybrid MAC protocol, BN-MAC [30], provides a potential solution for mobile nodes and dynamic network patterns. Idle listening time is reduced, and packet collision issues are avoided to reserve energy for extended network lifetime. The partial synchronous scheme plays an important role in time delay mitigation to obtain channel access during the contention period. The BN-MAC also leverages the scheduling mechanism to perform conflict-free communication and diminish the overhearing problem. On top of that, several advanced modellings are invented and implemented to collaborate with the BN-MAC protocol to extend the sleep period and shorten the packet forwarding path as much as possible.

- **AP-MAC**

The asynchronous MAC protocol with low duty-cycle and high energy efficiency in [31] provides a feasible solution for a flexible scheduling mechanism based on estimated traffic conditions. The AP-MAC protocol [31] allows each node to wake up randomly according to a predefined wake-up algorithm to avoid failed transmission caused by packet collision. Furthermore, it enables energy conservation via using a low duty-cycling scheme and enhances the transmission efficiency at the same time. In order to establish a reliable connection between the sender node and the receiver node, it is necessary to ensure nodes to convert between the wake-up period and sleep period as scheduled in advance. AP-MAC leverages the advantage of the adaptive low duty-cycling scheme to make communications both robust and resilient.

- **SLACK-MAC**

SLACK-MAC [32] is proposed using low duty-cycling with maximum 1%. In order to mitigate the possibility of transmission collision or cross-talk effect, the time scheduling of active period and inactive period is designed based on past experiences. The history of successful packet delivery has a crucial effect on the prediction of the subsequent sleep-wake scheduling design. Obviously, the time slot distribution among all nodes is not uniform, unlike random access. However, it is reported that the nodes selected in the past that are successful in data transmission have a relatively higher possibility to work again in the future. After a thorough evaluation process, the improved SLACK-MAC protocol works properly at an extremely low duty-cycle, and the delivery radio can be achieved up to 100% as the pending time spent to generate packets keep increasing. Essentially, the final result of end-to-end delay during effectual transmission process is relatively large (i.e., approx. 300–600 s), which cannot be tolerated in underground CAS design.

Scalability

- **SE-MAC**

In SE-MAC [33], the main improvement of communication network scalability is to have time delay mitigated significantly. Therefore, a novel modelling method called Adaptable Application Independent Aggregation (AAIA) was invented to reduce the overall latency. The AAIA model also encompasses cross-layer routing optimisation to further shorten packet delivery delay. The goal of the AAIA model is to make use of constrained power supply and channel bandwidth to perform packet delivery with maximum transmission efficiency using a unique data aggregation scheme. Moreover, there are four different aggregation functions implemented in this model, and they are also capable of alleviating overhead issues.

- **A Hybrid Protocol**

In [34], another solution to extend network scalability was introduced using a hybrid MAC protocol. The communication process provided by this MAC protocol can be divided into two different periods. One is used to contend for channel access and the other one is designed for data transmission. The contention period allows only one device to win the opportunity for pending packets to be sent in the subsequent transmission period using the p-persistent CSMA mechanism. The following transmission period employs the TDMA technique with an improved reservation scheme in channel allocation fairness. The proposed MAC protocol can achieve high performance regardless the size of different wireless sensor networks. Additionally, the refinement of several crucial parameters to balance the contention phase and transmission phase is complicated and has to be adjusted if the target application is changed.

- **SQ-MAC**

The scalable MAC protocol proposed in [35] is focused on the transmission of multimedia data traffic. It enables robust Quality of Service (QoS) support in addition to a limited end-to-end delay in its communication network. SQ-MAC [35] has a random access period to contend for channel access, which is similar with the previous hybrid MAC protocol, and it is subsequent to the scheduled access period using a particular reservation scheme. The reservation-based transmission stage is important to maximise network scalability based on optimum channel utility. This protocol provides a reliable and resilient solution using an adaptive time scheduling method to reserve time slots for following practical packet transmission. The idea of the switching period is designed for broadcasting and makes each sensor node aware of the time slot assignment of the subsequent transmission period. In order to increase channel throughput and network scalability, all free slots can be occupied without energy waste.

Handling Mobility

The design of Depth First Search (DFS) is applied in [36] to perform time slot assignment, and making use of the Fault Tolerant Slot (FTS) enables the protocol to be adjusted under different node patterns [36]. Another method handling mobility and offering a novel approach to cope with dynamic active zones around the mobile nodes based on the specified speed threshold [37]. The MS-MAC provides maximised energy efficiency regardless of static or dynamic application scenarios [37].

Wake-Up Radio Enabled

In [38], a low-power device TICC1200 (i.e., short for CC1200) was used to keep listening and detect node mobility. It is also capable to wake up ultra-wideband (UWB) devices over a relatively long operation range to perform two-way ranging promptly. Although the system in [38] is designed for inventory management, and devices are mounted on an unmanned aerial vehicle which has higher flexibility in terms of nodes movement compared with V2V or V2P, collisions occurred in underground mines. The employment of external wake-up devices alleviates the crowded resource occupation caused by control frames for the time scheduling mechanism. It also provides mitigated overall time delay and system capacity.

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