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Network for hypersonic UCAV swarms

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Abstract Unmanned combat aerial vehicles (UCAVs) that swarm with both autonomous decision-making and cooperative attacking have been regarded as revolutionary elements of modern warfare. In such a swarm, inter-group connectivity must be ensured in a network to maintain a collective consensus. In recent years, academia and industry have made many efforts to achieve common tactical data link systems and commercial drone networks. However, the existing results have difficulty meeting the needs of cooperative autonomous UCAV swarms with both hypersonic mobility and time sensitivity in severe confrontation scenarios. In this article, we conduct an in-depth investigation of the network used for the hypersonic UCAV swarms, which can be considered as a special form of mobile wireless network. Furthermore, faced with specific functional demands, we summarize the main challenges of designing this dedicated network. In addition, a comprehensive survey of potential solutions for the network design is presented. Lastly, we discuss the possible capabilities of the network given the current forefront of technology, as well as remaining challenges and open issues.

Keywords military communication, machine-to-machine communications, multi-UCAV networks, ad hoc networks, wireless mesh networks, unmanned aerial vehicles, cross layer design

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1 Introduction

Modern warfare has entered the information age, and the continuous development of information technology has caused combat units and their combat platforms to operate in ways unimaginable a few years ago. The unmanned combat aerial vehicle (UCAV) [1] has attracted considerable attention, and it is regarded as a weapon system that can help revolutionary new air forces expand their tactical mission options. With the aid of networked collaborative autonomy, a group of UCAVs can make long-range takeoffs to perform combat missions in highly contested environments. After ensuring that they stay away from the coverage of advanced air defense systems, the group of UCAVs can perform some swarm-like operations activities more safely [2].

1.1 Development of cooperative UCAVs

In the past half century, great efforts have been made in the research and development of UCAVs. Among them, one of the most popular technology trends is multi-UCAV cooperation technology. It is generally recognized that once multiple unmanned combat units form a collaborative team, the combat effectiveness

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of this team will far exceed any independent combat unit. In this subsection, some typical models of cooperative UCAVs will be chronologically introduced.

1.1.1 *Granit: the first networked guided weapon*

The P-700 “Granit” missile is the world’s first networked unmanned aerial unit designed by the former Soviet Union in the 1970s [3], which creatively integrates network communication function modules and a unique cooperative guidance tactic system, enabling a group of four to eight missiles to be launched in a salvo. When these missiles approach the target, one of them climbs to a higher altitude and uses active radar to obtain target information, acting as the “leader”, while the other missiles stay at lower altitudes as “followers” and maintain radio silence. The leader provides course updating to the followers via communication links. Once the leader is destroyed, another missile must be capable of automatically replacing it. Because the above-mentioned “leader-follower” strategy can effectively improve the survivability of the formation, the connectivity and autonomy of the Granit missile are impressively advanced for its time.

1.1.2 *Tomahawk: network-centric capability*

The U.S. navy’s long-range, all-weather subsonic missile “Tomahawk” was developed in the 1970s [4] and first operationally launched in the Gulf War in 1991. It was initially designed with a “fire-and-forget” mode, which constituted one of its primary drawbacks [5]. To mitigate this drawback, in 2004, the upgraded Tomahawk had network-centric warfare capabilities, which can realize “man-in-the-loop” control in flight. The key technology of this upgrade is the two-way communication between the missile in flight and the control nodes via satellite [6]. Data from the missiles provide real-time health status reports and battle damage indications, while reverse links allow operators to send commands to divert or alternate targets based on the effectiveness of previous missiles. Furthermore, in 2015, another upgrade [7] demonstrated that the latest version of Tomahawk is capable of taking a reconnaissance photo and transmitting it back to base, entering a loitering pattern, and following orders to re-target mid-flight.

1.1.3 *JSOW: network-enabled weapon*

In 2003, U.S. Air Combat Command headquarters introduced the concept of the network-enabled weapon (NEW), which was aimed to capacitate UCAVs’ interoperability. Relying on a common tactical data link, UCAVs can connect to external sensors and other networks to ensure they can obtain in-flight battlefield awareness updates of time-sensitive and moving target in all-weather, high-threat environments. NEW was viewed as the “single most cost effective means available for enhancing overall armament capability” [8].

This idea was adopted by the U.S. navy to enhance the combat efficiency of its anti-ship missiles. Since 2007, the U.S. navy has been investing in its strike common weapon data link program, which was aimed to upgrade the joint stand-off weapon (JSOW) and “Harpoon” weapon systems [9] that have network enabled data link capabilities. In addition, JSOW C-1 [10] has added a removable component with Link 16 weapon data link function, making it the world’s first network-enabled weapon.

1.1.4 *LRASM: cooperative as a swarm*

The long-range anti-ship missile (LRASM) program was scheduled to launch in 2009 to deliver a stealthy anti-ship strike with longer range and more sophisticated autonomous targeting capabilities. The program’s vision was to devise LRASMs capable of autonomous targeting independently of prior intelligence. It was designed to be capable of operating in a low-power emission and radar-standby mode. High fidelity off-board data from external sensors can be sent to it via wireless communication links, helping it to build a real-time electronic picture of the enemy battlespace, thus guaranteeing the missile to have a very high chance to reach its target area. Furthermore, it was also expected to work with other LRASMs,

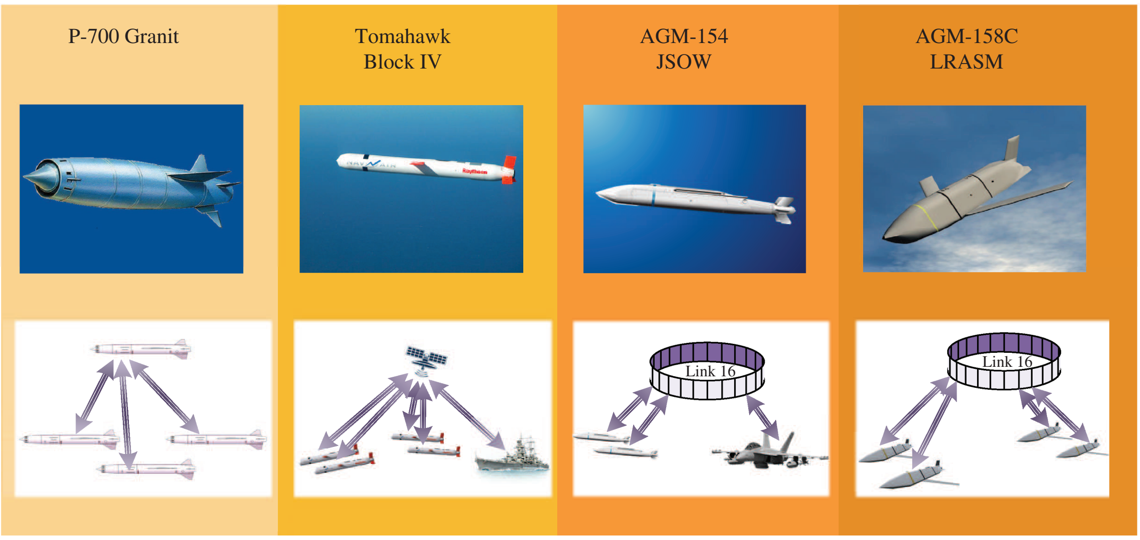

Figure 1 (Color online) A comparison of Granit, Tomahawk, JSOW, and LRASM in terms of their profiles and communication mechanisms.

as a swarm, to infiltrate and execute an attack cooperatively by using both their threat emission detection and geolocation capabilities and communicating among themselves in a real-time mode [11]. The communication mechanisms of Granit, Tomahawk, JSOW, and LRASM are compared in Figure 1.

1.1.5 *Future trend*

Existing UCAV communication systems usually require satellites, launch platforms, or other command and control (C2) units within their line-of-sight range, which poses a radical threat to the system's support units. More seriously, under extremely hostile operational environments, the reliability of the above architecture has also been severely challenged. To this end, the United States announced in 2014 its third offset strategy [12], which outlines five core technology components. One of those components was "Network-Enable, Semi-Autonomous Weapons Hardened to Operate in a Future Cyber/EW Environment".

In accordance with the third offset strategy, the U.S. army recently announced it was working toward autonomous coordination capabilities. In 2017, the missile multiple simultaneous engagement technologies (MSET) [13] program was initiated, which was envisioned as a suite of technologies providing supervised autonomous terminal engagement of multiple missiles against various targets and inter-group communication for shared situational awareness. It includes a digital data link network architecture that is capable of ad hoc network management, communication relay, and adaptable quality of services. Techniques and technologies such as low probability of intercept (LPI), low probability of detection (LPD), anti-jamming, advanced antennas, and transceivers are desired features of the network. It is not difficult to see that when UCAVs are organized as a coordinating group, they will provide more functionality than when running independently. In addition to enabling traditional saturated missiles to have the advantage of attacking heavy targets, the use of a revolutionary autonomous coordination strategy can also ensure that the missile can provide distributed operations and multiple operations with fault tolerance in a complex environment.

1.2 Motivation for a dedicated network for hypersonic UCAV swarms

Although methods for cooperative control of multiple UCAVs have been widely investigated [14], the communication conditions are rarely considered (or merely overlooked) as pre-set hypotheses. In this subsection, both the development status and remaining challenges of UCAV swarms' communication are outlined.

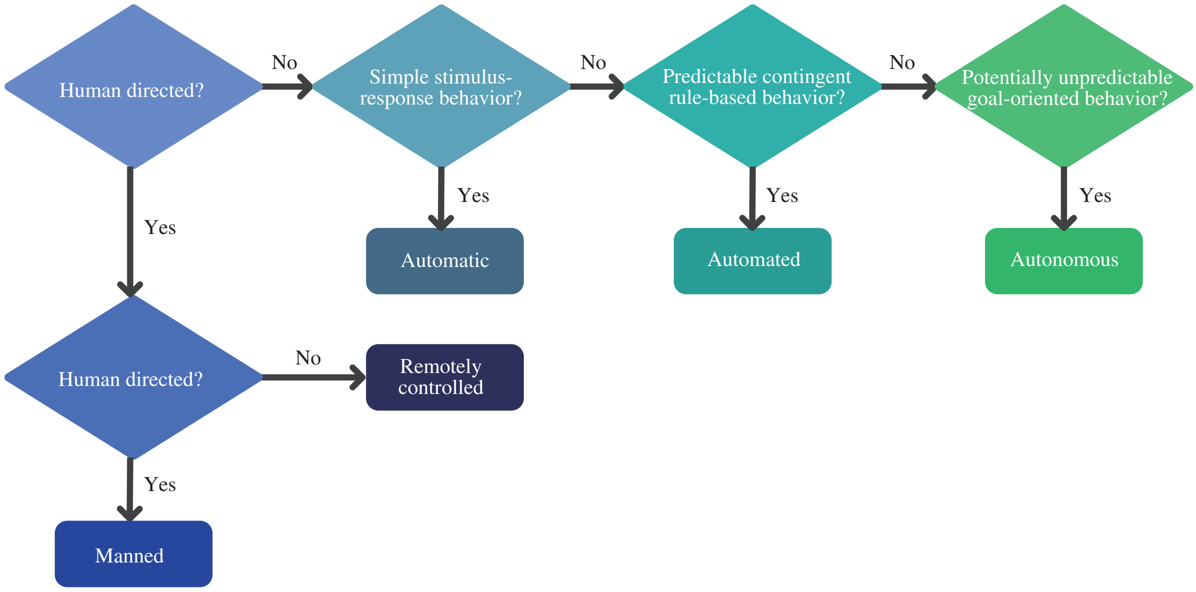

Figure 2 (Color online) Conceptual map of the terms related to "autonomy".

1.2.1 *Sophisticated coordination*

For a long time, the necessity of communication is often ignored, and the reason is likely owing to the simplified treatment of the leader-follower strategy. In this strategy, the group control problem can be reduced to a well-established single-agent control problem [15]: the leader usually uses single-agent path trajectory generation techniques, while followers use conventional tracking strategies. Based on this conventional philosophy, the formation flying control can be achieved without any intended information exchange. However, this leader-follower strategy is not suitable for more complex and autonomous utilities.

Strengthening UCAVs' autonomous execution capability is a general trend in formulating national defense policies and warfare. This development reflects on the progressive degree of sophistication of units' responses to external stimuli. A conceptual map is depicted in Figure 2 to help distinguish the concepts of the relationships between human direction and autonomy.

In "man-in-the-loop" type weaponry [5], such as earlier Tomahawk variants, unmanned combat units can be remotely controlled by the operator via a basic controller that displays sensor data of the target. The control process is likely to be completed through one-way or two-way links. Therefore, the concept of "man-in-the-loop" is bound to be limited by the response time and survivability of the operating platform, as well as the line-of-sight range of the communication links.

The "NEW" concept evolves by logging weapons into a common network with multiple platforms, thus allowing the control of weapons to be passed from one platform to another. It is undeniable that increased computerization in assessment and decision-making mechanisms can make tactical responses faster and more accurate. However, the widened connectivity is a double-edged sword: it can enable communication architecture with cross-platform compatibility, but this compatibility may follow Liebig's law of the minimum. The widespread use of a common waveform will inevitably increase the risk of signal detection.

Cooperative autonomy is regarded as a logical extension of network-centric warfare. A group of UCAVs with capabilities of both internal information exchange and swarm intelligence can automatically accomplish missions with limited prior knowledge about the target and battlefield environment. It enhances the utility of on-board sensors with collective intelligence technologies to achieve better situational awareness, thus reducing the dependence on external supporting units. With the optimized group composition and adaptive operation management, the combat efficiency of UCAVs can be substantially improved.

Table 1 Comparison for the features of wireless sensor network (WSN), mobile ad hoc network (MANET), tactical data link (TDL), and the proposed UCAV network

	WSN	MANET	TDL	UCAV network
Energy-saving demands	High	Low	Medium	Low
Minimization demands	High	Low	Low	High
Node mobility	Low	Medium	High	Ultra-high
Node count	High	Medium	High	Low
Delay tolerance	High	Low	Low	Ultra-low
Topological changing	Rare	Frequent	Medium	Frequent
Network lifespan	Days	Minutes	Minutes to hours	Seconds

1.2.2 *Insufficiency of common tactical data link systems*

The network-enabled weapons being developed currently are generally designed with common tactical data link systems [9], which are the products of compromises.

Out of a trade-off between cost, antenna size, rain-fade resistance, and spectrum availability, the common tactical data link systems usually operate on UHF (300 MHz to 1 GHz) and L (1 GHz to 2 GHz) bands, causing difficulties for the high-gain antenna array minimization and anti-jamming null-steering capabilities that are highly required by airborne communication devices.

The common tactical data links, by their nature, are accessible to a variety of participants. All the accredited units are allowed to access the network, and all the circuits functioning in the same area simultaneously are allowed to share the same bandwidth. This inherent accessibility may cause inefficiency and waste in resource utilization: the channel must be split according to different system requirements, thus making the overhead of network maintenance very high. In a joint engagement, which involves various units and lasts hours or even days, network maintenance becomes necessary and beneficial. However, future UCAVs are expected to fly at a hypersonic speed, in which case the swarm engagement may only last up to hundreds of seconds, making the network maintenance cost in terms of common tactical data links potentially redundant or even harmful.

The biggest drawback of common tactical data links comes from their vulnerability to electronic countermeasures. Of course, there is no doubt that commonly used tactical data links have always been the primary goal of adversarial military intelligence measures. Taking modern high-performance air defense systems as an example, once an attacking unit communicates through a common tactical data link, its signals are easily detected, identified, intercepted, and blocked by the enemy, which will inevitably pose a serious threat to the fulfilment of the operation. A comparison of the features of wireless sensor network (WSN), mobile ad hoc network (MANET), tactical data link (TDL) and the proposed UCAV network is depicted in Table 1.

1.2.3 *Network for hypersonic UCAV swarms*

In view of the aforementioned problems, a promising alternative solution is to construct a wireless communication network architecture that is specifically designed for the hypersonic UCAV swarms and has finite compatibility and interoperability. By concentrating limited resources to implement a certain set of features, the network can support coordination functions beyond tactical demands, while also enabling design miniaturization out of technical constraints.

In this subsection, we briefly review the developmental history of UCAV swarms and their ever-increasing dependence on wireless communication technology. In the following, we will outline both the functional requirements and technical challenges of the hypersonic UCAV swarm-based networks. In Section 2, we generalize operational scenarios of hypersonic UCAV swarms with various degrees of cooperation and collective autonomy. In Section 3, we summarize the functional features of the dedicated network to support the sophisticated cooperation for hypersonic UCAV swarms. Although there already existed several studies that focus on the networks of flying unmanned aerial vehicles formation [16] or swarm [17], the proposed network is highly application-oriented and has unique design constraints. These advantages are beyond the reach of existing systems. In Section 4, the potential technological solutions for the proposed network system are introduced and compared. Lastly, the challenges and open issues are summarized in Section 5. To the best of our knowledge, this is the first comprehensive study of hypersonic UCAV communication networking.

2 Operational scenarios

UCAV swarms are designed for military missions. Depending on the mission task, operation tactics, and unit capabilities, the swarms may work on different cooperation methods, mainly including saturation attacks, shared situational awareness, distributed cooperative guidance, cooperative path planning, cooperative searching, and eventually fully functioning cooperative autonomy in contested environments. These methods and their requirements for communication networks are introduced in this section.

2.1 Saturation attack

In military exercise simulations, people often assume that modern and future swarm attack scenarios have multiple attack waves, and that multiple attack units may participate in each attack wave [18]. With the help of good self-organizing technology, a group of well-organized, low-cost UCAVs can often produce more powerful combat capabilities and effects than a single excellent UCAV. Take saturation attacks as an example: to gain operational advantages, each round of attack requires multiple collaborating units to hit the target simultaneously and use of powerful technical capabilities to suppress the effective response of the defending side. Such saturation attacks have been devised as an effective countermeasure that can survive the threat of interceptors and penetrate defense systems with powerful surveillance and firing capabilities [19].

A thoroughly discussed saturation attack strategy is the aforementioned “leader-follower” mode [20]. In recent years, some more complex strategies have attracted progressively more attention from both military and academia. Owing to the capability of flexible flight paths, UCAVs are expected to engage in a multi-directional attack on one target [21], thus imposing additional geometric requirements on the defense side [22, 23]. As an extension of the “leader-follower” mode, the heterogeneous attack can be described as follows: a high-performance UCAV independently searches for attacks targets, while other low-cost UCAVs adaptively follow the leader in a coordinative manner [24]. The above strategy has obvious advantages when facing highly maneuverable targets because the technologically advanced leader has the ability to track the targets, while the following UCAVs can ensure attack success with a quantitative advantage.

2.2 Shared situational awareness

Situational awareness comprises knowledge regarding friendly units, the enemy, the battlefield environment, and the combat intent. The degree of shared situational awareness is determinant for collective intelligence.

To maintain the saturation dominance, cooperating UCAVs may be launched by plural platforms from different directions while carrying divergent information. Therefore, information fusion would be necessary to provide a comprehensive picture of developing situations together with findings from other systems for further operation planning.

Owing to the impact of the hostile environment, coordinated flight plans are unlikely to be calculated or distributed offline by a central entity to others. Instead, members must take their own decisions concerning their next action [25] while simultaneously understanding the condition of their colleagues. It requires the transfer of necessary data to be available in a timely manner for a multitude of entities. Furthermore, the information must be properly understood by each other within the context of the joint mission [26].

For their tactical utilities, UCAVs are equipped with various types of on-board sensors, including radars, accelerometers, gyroscopes, and electro-optical/infrared cameras. Therefore, the payloads of intra-group communication have diverse representation formats, data sizes, and traffic priorities. Consequently, configurable bandwidth and differentiated service capabilities are highly demanded.

2.3 Distributed cooperative guidance

The purpose of implementing multi-UCAV cooperation is to overwhelm defense systems by using quantitative superiority. It is usually required that some or all the UCAVs arrive the target simultaneously [27]. The guidance of simultaneous attacks can be achieved in two ways: individual homing and cooperative homing [14]. Following an impact-time-control guidance law [28] and a sliding mode-based impact time and angle guidance law [29], the impact time is pre-programmed into each member before its launch. Each individual does not need to communicate during the flight, so it is clear that units using this model cannot adapt to changing situations. With more on-board and in-flight communication resources, both centralized and distributed algorithms were proposed [30] and compared [31]. The centralized architecture, in which a coordination manager (leader) is designated to collect and broadcast the rendezvous time to all the other individuals performed better in terms of immediacy of group decision. In contrast, in distributed architecture, we assume that each individual is only allowed to communicate directly with its close neighbors, and eventually all members in a given swarm reach a common consensus. Distributed schemes are more practical, but group members often need longer time to complete group decisions than in centralized control schemes.

In cooperative homing, the attack efficiency and formation stability rely on both the reliability and robustness of the network. Even under a relaxed constraint, the majority of the nodes may be assumed to remain in the network until the moment of arrival [18]. In other words, the network must adopt an appropriate architecture to guarantee that it survives and functions normally even in an extremely contested situation.

2.4 Cooperative path planning

On-board path planning requires UCAVs to both obey a planned course but also to react to their environment by relying on sensing, communicating, and cooperating capabilities [32]. Numerous studies have been conducted to emphasize that information sharing plays an important role in cooperative path planning. One of the main requirements in successful cooperation and coordination is that the members must be capable of communicating during most of the mission [33]. Those studies usually simplify the connectivity condition as a physical distance constraint [34]: once two nodes stay inside a common geographic range [35], unlimited communication between them must be guaranteed. Consequently, the communication problem is integrated with another important problem, i.e., the path planning optimization problem. However, in practical scenarios, the direct communication link between two nodes is likely to be subject to various types of disturbances. In this case, information sharing must be achieved with the help of more sophisticated networks, especially with multi-hop relay technology. In this case, network latency and traffic restrictions will affect the stability of formation control [36].

2.5 Cooperative searching

Traditionally, target surveillance can be accomplished by using sophisticated radar systems. However, in a highly contested environment, such support might be unavailable. More importantly, the close reconnaissance may be too risky, forcing engagement to be initialized with a deficient in knowledge of the targets. To address these challenges, we may enable the attacking UCAVs with reconnaissance capabilities. For instance, during an exercise [7] in 2015, the Tomahawk missile demonstrated the ability to capture a photo of battlefield by its on-board camera while operating in a loitering pattern, transmitting it back to the base and awaiting mid-flight re-target orders. From a more practical point of view, the Tomahawk is designed for multiple contact missions. The design idea is to throw the first or first few members into an uncertain area as torches to illuminate the road for subsequent members.

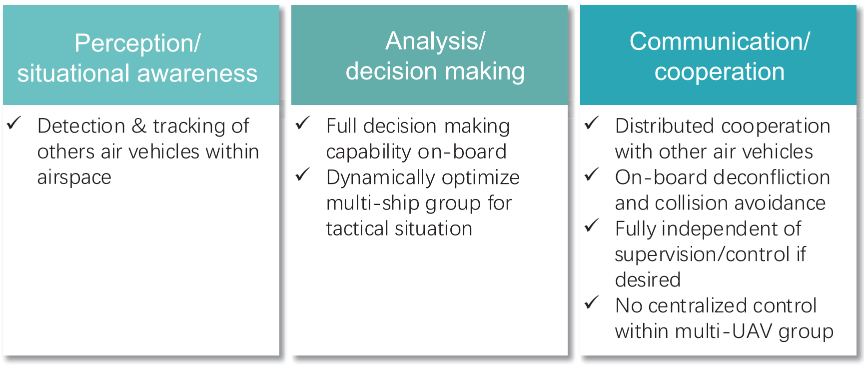

Figure 3 (Color online) Features of a fully developed autonomous multi-UCAV.

The rapid development of artificial intelligence has made it possible to establish more effective solutions for collaborative searching. In this scenario, the ultimate goal of each entity in the team is to obtain as much information as possible about the area of interest and to determine the location of potential targets based on this knowledge. Each member stores a map of the probability distribution of the target position and updates the map in real time based on the shared sensor observations obtained during the task execution. The advantage of this method is that it has a high degree of scalability and real-time adaptability. Even so, this method requires unlimited network connectivity to ensure that each node can connect to the network, and with the help of powerful communication capabilities, the global information state of the world is reconstructed at each node location [37].

2.6 Cooperative autonomy in contested environment

Despite the steady development of multi-agent control technology in recent years, its main methodologies for information transfer are still limited to pre-programming and radio remote control [38]. On the other hand, military tactics require UCAVs to take off from a standoff range, survive in severe electronic warfare environments, and successfully navigate to uncertain areas. Unfortunately, the conventional methodologies are insufficient to address the emerging problems in multi-UCAV cooperation. Evidently, it is necessary to explore more autonomous approaches.

Fundamentally, an autonomous system [12] is defined as a system that can independently form alternative solutions based on its knowledge and understanding of the world, the local dynamic environment, and itself, and make choices to accomplish its stated goals.

Weaponized autonomy is an overarching enabler of future warfare. The U.S. Air Force Research Laboratory announced autonomous control level metrics [39] to evaluate the degree of collective autonomy. The features of a fully developed autonomous multi-UCAV are elaborated in Figure 3. To make such autonomous functions possible and play an active role in UCAV group operations, inter-group communication will undoubtedly play a vital role [40].

3 Functional features

As mentioned above, with the help of the network, the system is able to pass telemetry information and commands between the controller and UCAVs in a manner similar to a conventional two-way weapon data link. Furthermore, just like a vehicle ad hoc network (VANET), it is capable of offering peer-to-peer information connections. It also collectively supports environment sensing and collaborative consensus, like a WSN. Consequently, this hypersonic UCAV swarms-based network shares some common characteristics with the existing network architectures, without loss of its distinguishing features. A comparison of the communication networks is diagrammed in Figure 4, followed by analysis of their features in subsequent subsections.

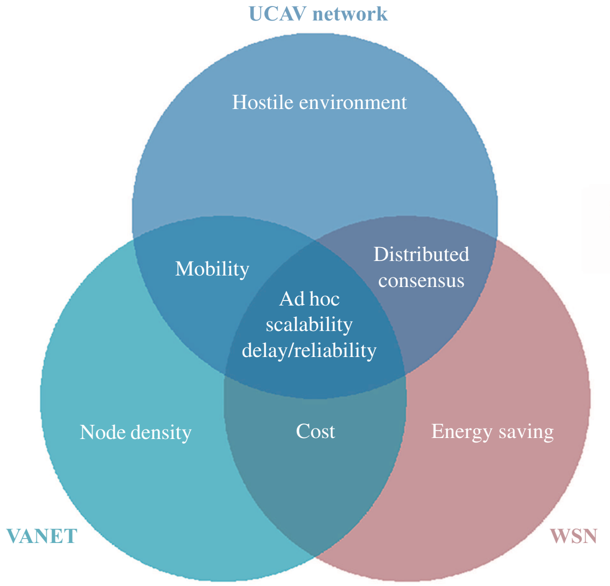

Figure 4 (Color online) A Venn diagram that illustrates the relationship between VANET, WSN, and hypersonic UCAV swarm-based networks.

3.1 Ad hoc

In the conventional weapon data links, it is assumed that the external infrastructure (e.g., fighters or relay satellites) is in line of sight, which limits the operational range of the system. Taking off from the line of sight is an important feature that UCAVs urgently need because in actual combat scenarios, there is no guarantee that there are available satellite resources in the battle zone. One of the advantages of autonomy comes from its independence from external support. In this sense, networks used in combat missions must be established without any infrastructure.

An ad hoc network is the cooperative engagement of a collection of mobile nodes without relying on the intervention of any centralized access point or existing infrastructure [41]. Ad hoc architecture has been admittedly applied in several scenarios such as unmanned vehicles and sensor networks [42].

3.2 Mobility and scalability

Node mobility and scalability are a priori design constraints in unmanned vehicle networks. The relative location and connectivity between nodes are constantly changing, resulting in time-variant network topology. In recent years, plenty of studies have been dedicated to designing protocols that are capable of adapting to the dynamic ad hoc topology. Simulations have verified the effectiveness of VANET methods under nodal motion constraints [43]; however, the relative velocity is generally assumed to not be beyond 150 km/h. In contrast, it is reported that Russia's latest anti-ship guided weapon can accelerate to Mach 9 (higher than 11000 km/h). Evidently, the protocols under VANET architecture cannot be directly applied to hypersonic UCAVs. It is a challenging task to develop efficient protocols for an ad hoc network formed by hypersonic vehicles.

Scalability constitutes another key problem in wireless sensor networks. In most scenarios, sensors are deployed randomly over a wide and complex terrain. The communication network must be adaptive regardless of the number of nodes, and it must also be flexible enough to easily incorporate other nodes into the existing architecture [44]. In sensor networks, because the relative positions of nodes are relatively stable, the scalability of the network is equivalent to achieving flexible coverage changes on a large geological scale, and for many nodes, these nodes are accessible. In contrast, although the number of nodes in the UCAV swarm is much smaller than most sensor networks, the former has a much larger geological distribution compared to the latter. For example, the U.S. navy's LRASM has a range of 1600 km [11], with the capability of communication with the shooter through a two-way satellite data link. To provide connectivity over comparable distances by multi-hop relays, the coverage of hypersonic UCAV swarm network must reach a much larger radius than that of most sensor networks.

3.3 Distributed consensus

Distributed consensus is an essential attribute of wireless sensor networks. The applicative scenario is usually a collection of sensor nodes with limited memory, and its computing resources are randomly deployed to the application site to obtain relevant environmental data [45]. In this case, data generated from neighboring sensor nodes are often redundant and highly correlated. Furthermore, the amount of data obtained by massive nodes can be enormous. Therefore, it would be impractical to assemble all data together for fusion [46]. Instead, research has focused on deriving a globally unitive estimation of parameters of interest in a distributed fashion [27, 47], which significantly reduces the amount of communication required and apportions the computation cost.

3.4 Delay and reliability

Low delay and reliability are commonly desired characteristics in all kinds of data communication. However, these features are of unparalleled importance here because important information in the network is often very time sensitive. Generally speaking, transmission reliability can be facilitated by using the automatic repeat request (ARQ) mechanism: if any data corruption is detected at the destination, the source must resend this packet. Although ARQ schemes are widely accepted in ad hoc networks owing to its simplicity and higher reliability [48], the retransmission extends the end-to-end delay, in which case the highly dynamic connectivity might even further increase the routing hop count. In addition, another commonly used method of error control is forward error correction technology: the sender (or source) encodes the information in a redundant way by using error-correcting codes to reduce the probability of error after decoding at the receiver (or destination). Admittedly, longer block lengths usually lead to better correction performance, but they also lead to greater processing delays. In sum, in the above two methods, delay and reliability are often intertwined, and the two are competing factors in implementation.

In the area of commercial communication, with the rise of fifth generation wireless systems (5G) and Internet of Things (IoT), the concept of ultra-reliable low-latency communication (URLLC) was proposed [49], which requires an end-to-end latency within a few milliseconds and an error probability as low as 10^{-5}. Recently a number of studies have been focusing on latency and reliability, including channel coding [50], framing/packetization [49], and MAC layer protocol design [51].

3.5 Hostile environment

Hostile environment is the key feature that distinguishes UCAV networks from other commercial wireless communication systems. Because the UCAVs are designated to attack the tactically important targets, the swarm must be prepared to confront advanced defense systems. For air defense systems, countermeasures against electromagnetic signals generally include detection, interception, and jamming techniques. Correspondingly, the network must have LPD, LPI, and anti-jamming capabilities.

LPD/LPI, or covert communication, is mainly achieved through randomization. By this means, signals may hide under noise or other irrelevant signals to be imperceptible. Randomization can be implemented in two ways: (1) burst transmission, which divides messages into several short packets, and then transmits signals in a sequence of small irregular time durations to avoid detection; and (2) the spread spectrum technique, which modulates the message using pseudorandom sequences to mimic the existence of noise.

Anti-jamming is permanently a central topic in the area of military wireless communication owing to the exposed nature of electromagnetic propagation and the rival nature of warfare. Prevalent anti-jamming methods include spread spectrum [52], channel coding [53], and adaptive directional beams [54]. In hostile environments, the most important countermeasures conclusively are the spread spectrum techniques, which have been widely adopted by numerous systems such as tactical data links.

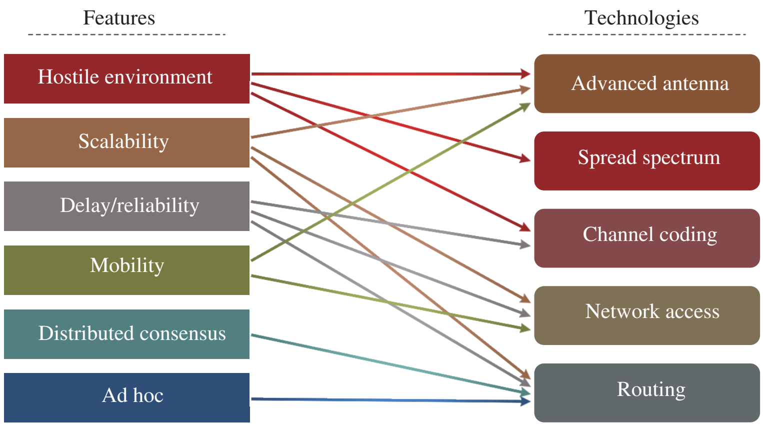

Figure 5 (Color online) A relationship map between the proposed technologies and the desired features in the network for hypersonic UCAV swarms.

4 Technological solutions

In this section, a set of wireless communication techniques are presented as potential solutions. These technologies cover many fields such as antennas, spread spectrum, channel coding, network access protocols, and routing protocols. The relationships between the technologies and the system features mentioned in previous section are demonstrated in Figure 5. In addition, in this section, we will conduct in-depth research on the latest progress of related research, and perform performance evaluations of related technologies based on the necessary features listed above. In addition, the open issues and technological challenges are summarized.

4.1 Advanced antenna array

Modern communication systems widely use antenna arrays and beamforming technologies. These technologies can adaptively optimize the beam pattern by adjusting array weights, thereby achieving spatial selectivity of signal propagation [55]. The transmitter can create one or more directional beams directed to the corresponding device by adopting the method of "experiencing constructive interference at a specific angle" when combining the array signals. The advantage of this method is that it can force the limited transmission energy to be concentrated in a narrow angle, thereby greatly reducing the likelihood that the signal (or beam) will be detected by malicious users [56]. Similarly, the receiver can only admit signals coming from a distinctive angle, and by "processing the array signals as destructive interference", the receiver can eliminate (unwanted) signals coming from a specific angle.

4.1.1 *Spatial selectivity*

The solution based on beamforming's spatial selectivity can effectively mitigate the impact of hostile interference and ensure that the frequency equipment still has a sufficiently high signal covertness in hostile environments.

From the perspective of the transmitter, if we have learned the directional information of the attentive receiver or hostile jamming, the transmitting beam should be focused at a specific angle to avoid exposure to enemy monitoring equipment. If a directional antenna is capable of providing the same effective isotropic radiated power (EIRP) in the direction of the receiver as an omni-directional antenna, its probability of detection can be reduced by over 90% [57]. Similarly, from the perspective of the receiver, if we already know the direction of arrival of the desired signal or information about hostile jamming, the receiver can only receive energy from the sender directions and simultaneously reject energy from the jamming directions. By focusing a narrow main lobe on the signal of interest while placing side lobes on other (i.e., off the main lobe) angles, it is possible to suppress jamming that is 20 dB stronger than the desired signal [58].

Antenna arrays with adaptive spatial selectivity potentially benefit the scalability of network. The directional antenna generally has a much higher gain at the desired direction than an omni-directional antenna. For instance, it was shown in a verifying test that a four-element adaptive array may provide up to a 6 dB gain in margin [59], corresponding to 40% coverage range extension [60]. Furthermore, highly directional transmission is also capable of improving both capacity and accessibility of the network. In this case, users from different directions may be well separated using different spatial beams, thus enabling multiple nodes with different beams to simultaneously access the channel to significantly boost the multi-user capacity. The above-mentioned concept is known as space-division multiple access (SDMA) or beam-division multiple access (BDMA) [61]. In SDMA, a new entry establishes new links by claiming new beams (generally without disturbing existing links) [62], rather than invoking local or global topology rearrangement as time-based or frequency-based multiple access methods.

4.1.2 *Navigation-added beamforming*

In narrow main-lobe beamforming methods, it is assumed that the direction of the signal of interest is previously designated or estimated. Although there are many theories regarding the direction of signal arrival estimation [63], those methods might not be feasible here mainly owing to the intentional covertness of the signal. Alternatively, the signal direction can be calculated based on the relative location between the sender and receiver. Of course, in most of the VANET and sensor networks, the location information is provided by the satellite-based navigation system. However, the satellite services are not always available in conflicting regions. Instead, autonomous relative navigation has been proposed to address this issue. In those schemes, if peer-to-peer range measurement is available in an ad hoc network, either a distributed or a centralized location estimation algorithm can be implementable [64]. Currently, relative navigation has become a key facility of many tactical data link systems [65, 66], and the beamforming technique is potentially applicable.

4.1.3 *Null steering*

Null steering, or zero-forcing, is regarded as a classical and effective method of antenna array against strong interference. In long-distance transmission and harsh environments, the desired signal might hide under the background noise, making estimations of its direction of arrival difficult. But the power of the jamming signal is usually much stronger than the desired signal or the background noise, so its angle of arrival can be easily estimated. Using suitable constraints, beamforming can adaptively produce a radiation pattern with deep narrow nulls in the directions of interferences [67]. Considering the mobility of hypersonic UCAVs, the relative direction of jammers may continuously change, resulting in a null-steering mismatching and a degraded performance. To overcome this problem, some improved algorithms have been proposed by broadening the nulls to enhance the robustness of their interference cancellation [68].

4.1.4 *Millimeter wave*

Device minimization is widely recognized as a challenging task for antenna array implementation and array design, in which the antenna elements are usually placed at approximately half-wavelength spacing. For instance, the spacing of early arrays at UHF and L-bands could be around 6–12 inches, which is unacceptable for the size-limited UCAV platform. To reduce the size of antenna array while maintaining a narrow beam width, we may choose a higher operation frequency to reduce the half-wavelength of the signal. The benefits of using higher frequency bands for signal transmission are not limited to this. In commercial mobile communication systems, people are beset by increasingly tight spectrum resources. If new spectrum resources in higher frequency bands can be used, the spectrum shortage problem can be effectively solved. Figure 6 illustrates the spectrum allocation of important civilian signals, which constitute the potential interference throughout the network.

A promising solution for the aforementioned challenge is to employ millimeter-wave (mmWave) technology [69]. Communication on mmWave bands from 30 GHz to 200 GHz has been proposed as an

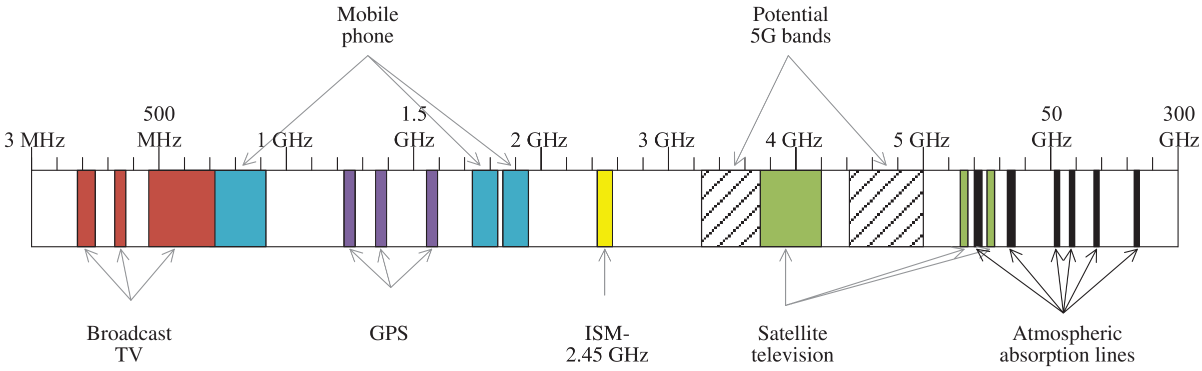

Figure 6 (Color online) Important civilian signals and absorption lines on the spectrum between 3 MHz and 300 GHz

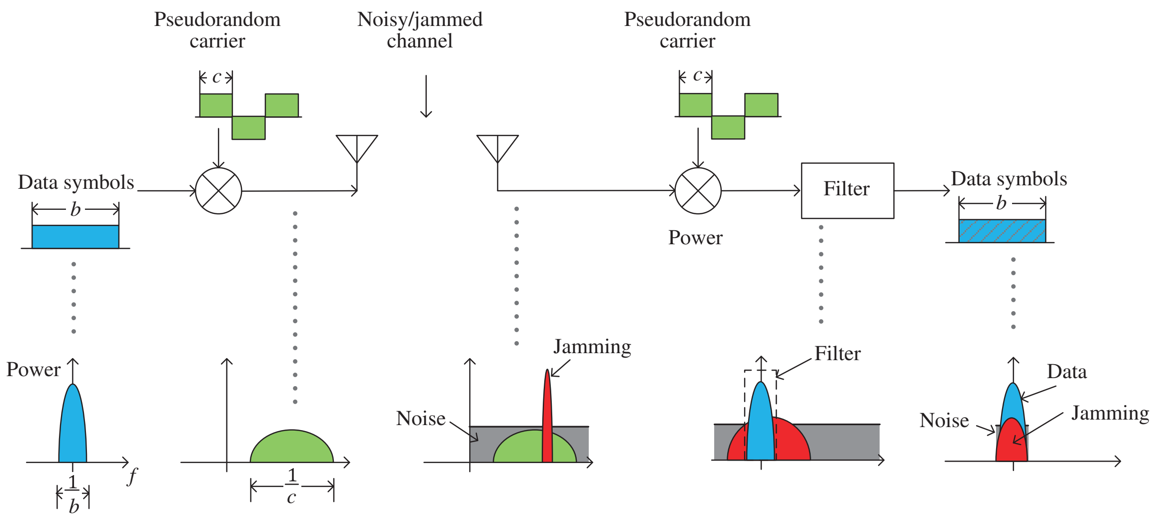

Figure 7 (Color online) The processing diagram of a spread spectrum system in a noisy and jammed environment.

important part of both the 5G wireless networks [70] and UCAV communications [71]. As the wavelength becomes smaller, electronically steerable antenna arrays can be realized as compact as a pattern of metal on circuit board [72]. Today, mmWave communication is at the turning point from concept to implementation, and several fully integrated mmWave systems have been reported (the interested readers may refer to [73] for details).

4.2 Spread spectrum

Spread spectrum has been regarded as one of the most important techniques in military radio communication. It is a kind of signal structuring method by which a signal can be generated with a bandwidth that deliberately spreads in the frequency domain, thus resulting in the occupation of a much wider bandwidth than the original information. This blunt abuse of spectrum resources has been well rewarded with both the lower power density in the frequency domain and noise-like waveform in the time domain, thus significantly reducing the probabilities of detection and interception, as shown in Figure 7. Furthermore, by properly correlative reception and filtering, the unwanted components in the receiving signal can be removed (while the desired information is recovered), enabling good anti-jamming and anti-interference performances. All the aforementioned capabilities give spread spectrum incomparable advantages in hostile environments.

The spread spectrum methods used in actual systems can be roughly divided into three categories: direct-sequence spread spectrum (DSSS), frequency-hopping spread spectrum (FHSS), and DS/FH hybrid spread spectrum (DS/FH-HSS), which are distinct by their carriers. A DSSS system uses a string of time-domain pseudorandom noise-like code chips as a carrier, while a FHSS system has a carrier that frequency shifts rapidly in a pseudorandom way. In contrast, DS/FH-HSS, as a combination of above two methods, modulates symbols with both time-domain chips and frequency-domain shifting carriers.

4.2.1 *DSSS*

The performance of DSSS systems heavily depends on the applied spreading codes, which have been thoroughly studied in past decades. The autocorrelation and cross-correlation properties of the spreading codes provide not only good noise-rejection capability [74], but also the opportunity for simultaneous multiple user access and relative ranging [75]. One of the most-used types of pseudorandom sequences is the maximum-length sequence (m-sequence), which has a simple generation mechanism and good correlation. However, m-sequences are periodical and predictable, resulting in a transmissions that are not completely secure. Although the performances of several other codes are comparable to that of m-sequences, research results show that these codes cannot solve the security problem [76].

To address the security issue, we may employ chaotic spreading codes to enhance the physical layer security of DSSS methods. A chaotic system is a type of nonlinear system that appears deterministic yet aperiodic, with some chaotic maps (e.g., Logistic, Chebyshev, Baker) having ideal noise-like properties. Because the synchronization in chaotic systems is first realized, a large number of chaos-based DSSS systems have been proposed and investigated, claiming good performance on both security and reliability (of course, most of them are relying on ideal abstract models). The main challenge with chaotic DSSS resides in code generation [77]. Reliable electronic hardware implementations of chaotic sequence generators based on recursion of maps by linear analogue functions are currently impossible owing to the manufacturing difficulties [78]. Fortunately, several modified and alternative approaches based on digital nonlinear functions were proposed and proved to have satisfying performances [79]. Despite this, recent studies have proved that chaotic sequences can be observed and recovered by blind detection methods based on the estimation of symbol periods [80]. To overcome this vulnerability, new chaotic DSSS methods using varied symbol periods [81], high-dimensional maps [82], or fake users [83] have been proposed, showing good pseudorandom characteristics and high capability of withstanding attacks.

4.2.2 *FHSS*

FHSS is a classical and meritorious technique that has been employed in military communications. By employing a carrier that agilely shifts between different frequencies, FHSS signals are unintelligible to the unauthorized inceptor, detector, and reactive jammer. As for constant jamming, in which the jamming signal is fixed on a frequency, a FHSS signal may only be corrupted for a short duration of time duration when the communication signal falls into the same frequency as the fixed jamming signal, leaving the majority of the signal untouched.

The covertness of FHSS relies on the speed of its carrier frequency shifting. The hopping carrier is traditionally conducted by phase-locked loop (PLL) circuits [84], in which the unavoidable settling time after frequency switching limits the hopping rate to below 1000 hop/s. A direct digital synthesizer (DDS), on the other hand, has faster switching speed; however, it is stuck with a high spurious level and high phase noise. Recently, combined PLL and DDS synthesizers have been widely investigated. The combinational solution obtains the merits of a wider band, a faster switching speed, a higher resolution, a lower spurious level, and phase noise [85].

The interference rejection capabilities of FHSS are dependent on its total occupying bandwidth. With the abundance of frequencies in the hopping pattern, there is only a fraction of time slots when interference and communicating signal overlap in the same frequency, while in other time slots, the interference can be suppressed by frequency selecting filters.

If in each time slot there are transmitted plural data symbols, which is called slow frequency hopping (SFH), those symbols are all affected when the overlapping happens owing to burst errors. To eliminate burst errors, we need to implement additional interleaving and length-extended channel codes, both of which extend the transmitting delay. In contrast, in fast frequency-hopping (FFH) schemes, one data

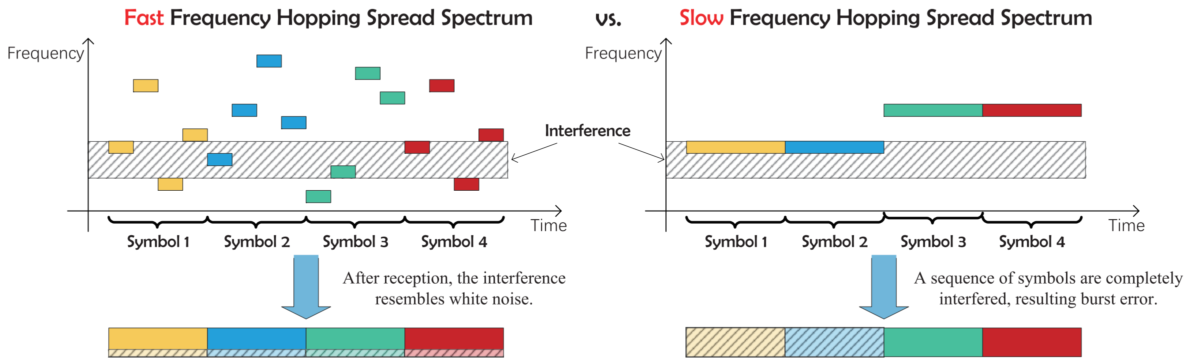

Figure 8 (Color online) The illustration of FFHSS and SFHSS schemes under narrow-band constant interference.

symbol is divided over multiple hops, giving the errors more random-like statistical characteristics and making error correction of channel codes easier. The difference between FFHSS and SFHSS is illustrated in Figure 8.

The drawback of FFHSS is that the phase-coherence within a symbol is hard to maintain. Almost all the studies assume that noncoherent reception is unavoidable, which has a poor performance in long-distance transmission under high mobility. In contrast, coherent FFHSS systems may perform better [86], but their synchronization and reception are difficult and seldom used. Owing to improved digital integrated circuits and microelectronic techniques, the direct-conversion FFHSS signal modulator emerged [87], in which the coherent fast frequency-hopping signal can be generated using a field-programmable gate array (FPGA). Despite all this, the independent coherent synchronization and reception of FFHSS is still an open issue.

4.2.3 *DS/FH-HSS*

The DS/FH-HSS system can be regarded as a combination of the aforementioned two schemes. In DS/FH-HSS, symbols are successively modulated by pseudorandom codes and frequency-hopping carriers to leverage the best features of frequency hopping and direct sequence spreading. Studies showed that a hybrid direct sequence/slow frequency-hopping (DS/SFH) system could reduce the probability of error as compared to both a DSSS system and a SFHSS system under the presence of multiple-tone jamming [88]. The multiple-access capability of DS/SFH-HSS has also proved to be superior to that of purely FHSS [89]. Its signal has excellent potential measurement performance in terms of distance and velocity [90], which provides a feasible basis for relative navigation and telemetry functions. Furthermore, the Link 16/Joint tactical information distribution system (JTIDS), a common and extensively applied tactical data link used by NATO allies, adopted a DS/SFH-HSS scheme for modulation [91].

Admittedly, the hybrid scheme unavoidably inherits some shortcomings of the systems off which it is based. Similar to pure FHSS, DS/SFH-HSS suffers from phase coherence difficulty and burst error problems. Currently, the JTIDS waveforms are received in a noncoherent way at the chip level. If a coherent demodulation is realized in the JTIDS, the data rate could be doubled [92]. As for error control, the JTIDS uses Reed-Solomon (RS) code, which is powerful for burst error correction (but may still introduce a process latency).

Because the direct-sequence/fast frequency-hopping hybrid spread spectrum (DS/FFH-HSS) scheme can synthesize the advantages of both DS and FFH technologies, it has been regarded as a robust secure transmission technique for communication in harsh environments [93]. However, the hybrid DS/FFH scheme has long been limited by the technique of high-quality frequency synthesizers. Fortunately, today's DDS with synthesizers that have extremely fast hopping speed is quickly becoming a replacement for traditional frequency-agile analog-based PLL synthesizers, relying on the output frequencies with micro-Hertz resolution and sub-degree phase tuning capabilities that can readily be generated by a single integrated circuit. Consequently, DS/FFH-HSS attracts wide attention in recent years. It is shown that DS/FFH-HSS outperforms the existing standard DSSS and FHSS methods on transmission reliability and security [94]. Furthermore, a hardware prototypic DS/FFH-HSS system was achieved on a single field-programmable gate array (FPGA) [95]. In the reception scheme of this prototype, the signal acquisition is accomplished by a correlator successively searching on all frequencies. However, this kind of serial searching method requires a long processing time. For UCAV swarm networks, burst transmission is an important function to improve signal concealment, so the acquisition efficiency of the above technology may become a bottleneck in system performance. Evidently, fast acquisition of DS/FFH-HSS in harsh environments and high mobility with limited on-board processing resources has constituted an extremely challenging issue.

4.3 Channel code

In scenarios where the ARQ scheme is not applicable, forward error correction technology has become the most important measure for error control, which directly determines the performance of the system. The central idea of forward error correction is to encode the transmitted information using redundant information, which can significantly improve the reliability of information transmission, allowing the system to reconstruct the transmitted information even if some of the information is lost. According to such features, channel codes preferably welcome short constraint length (or block size) and high reliability in noisy channels. Additionally, capability against burst errors is needed if the slow frequency-hopping schemes are adopted. In practical systems, designing channel codes with both short latency and high reliability is a challenging task because the two fundamental requirements are essentially conflicting, thus a delicate compromise is required [96]. There are several potential candidates to adopt, including Bose, Chaudhuri, Hocquenghem (BCH), tail-biting convolutional code (TBCC), turbo codes, low-density parity check (LDPC), and polar codes.

4.3.1 *BCH codes*

As mentioned earlier, the JTIDS uses RS codes for combating burst errors. RS codes belong to the family of BCH codes, whose main feature is that the number of guaranteed correctable symbols is defined during the code design process, regardless the combinations of errors. In this case, the BCH codes are effective against both burst errors and random errors. Recent advances in ordered statistics decoder (OSD) design [97] significantly reduce the decoding complexity, making OSD a good choice for decoding packets of short length (typically 256 bits) and very short length (no more than 32 bits).

BCH essentially belongs to the category of block codes (and polynomial codes) that operate over Galois fields. The block length, coding efficiency, and the amount of correctable errors are jointly constrained by the generator polynomial properties. Once the coding parameter selection is inflexible, it will affect the performance of higher-layer protocols and bring unnecessary delay.

4.3.2 *Tail-biting convolutional codes*

Unlike block codes, which are usually hard-decision decoded, convolutional codes can perform maximum likelihood soft-decision decoding with reasonable complexity. Another advantage of convolutional codes in contrast to classic block codes is that the former theoretically may have an arbitrary block length. In this case, convolutional codes may work on symbol streams and can be terminated at any length. Schemes of stream termination for convolutional codes include direct truncation, zero tail, and tail biting.

TBCC outperforms direct truncation by having all symbols affording the same amount of error protection, provided that a maximum likelihood decoder is utilized. Tail-biting codes are also capable of avoiding the rate loss in zero-tail termination; consequently, it is more suitable for adopting a shorter codeword length. The authors in [98] showed that TBCCs have great performance for short block lengths (64 bits or 128 bits), achieving block error rates that are remarkably close to theoretical benchmarks down to moderate and low block error rates.

Because the disadvantage of TBCCs resides in the complexity of maximum likelihood decoder, many researches have focused on low-complexity decoder design. In some of the recently proposed approaches [99], the average decoding complexity may even approach the ideal benchmark complexity.

4.3.3 *Turbo codes*

Turbo codes belong to the class of convolutional codes that are developed by parallel concatenating two identical convolutional codes blocks. Turbo codes are well known for their outstanding performance, which closely approaches the theoretical limits imposed by Shannon's theorem with much less decoding complexity than the Viterbi algorithm on the long convolutional codes under the same performance requirement. Turbo codes use iterative decoders to maintain a low complexity. Unfortunately, a shorter block length implies a lower performance. Turbo codes with iterative decoding in short and moderate block lengths show a gap of more than 1 dB to the finite-length performance benchmark [100]. There are attempts to improve the degradation by optimizing interleave design [101] and exploiting higher-order field [102].

Another problem with turbo codes is that their performance may be significantly eroded at very low values of bit error rates (e.g., BER $\leqslant 10^{-9}$). In fact, their free distance, namely the minimum Hamming distance between different codewords, can be low even with very large interleave lengths. The low free distance results in the BER curve flattening after entering the "error floor" region, making it extremely difficult to achieve a very low probability of error even if the signal-to-noise ratio continuously grows. Recent studies [103] showed that the aforementioned problem can be mitigated by adopting both interleave design improvements and cyclic redundancy check codes.

4.3.4 *LDPC codes*

LDPC codes are another set of well-known correction codes that closely approach theoretical performance limits. LDPC codes with iterative belief propagation decoding can perform very close to Shannon's limit with only a fraction of a decibel gap. Because their rediscovery in 2003, LDPC codes have been finding increasing use in applications requiring reliable and highly efficient information transfer over bandwidth-constrained links in noisy channels. Although the error floor problem is also met in LDPC codes, the authors in [104] showed that LDPC can achieve better performance for high code rates.

Binary LDPC codes with iterative belief propagation decoding do not perform well at short to moderate block lengths, mainly because the existence of many short cycles in the code's bipartite graph. Recently protograph-based LDPC codes have been shown to perform well under belief propagation decoding at short to moderate block lengths, although their performance is still not comparable with BCH codes under OSD or TBCCs with large memory. However, LDPC codes have the advantage of very low decoding complexity under iterative algorithms. Furthermore, the non-binary LDPC codes are also shown to perform very close to the finite length performance bound; however, this is at the cost of extra decoding complexity [105].

4.3.5 *Polar codes*

In the past decade, polar codes have attracted tremendous attention in both academia and industry. Polar codes belong to the family of linear codes that can provably achieve the capacity of a binary-input discrete memory loss channel using low-complexity encoding and decoding, as the code length tends to infinity. Performance of polar codes using various decoding algorithms, such as successive cancellation (SC) and successive cancellation list (SCL), has been systematically investigated. In SC decoding, it is shown that the block error probability decays exponentially in the square root of the code length, and the recursive nature may impose a large latency, making the SC algorithms unsuitable for low-latency applications [106].

A major improvement in decoding performance is achieved by using SCL decoding, which always keeps a list of most likely decoding paths (i.e., it is unlike the SC decoder, which keeps only one decoding path). The authors in [107] showed that with additional cyclic redundancy checks and systematic encoding, the SCL-decoded polar codes can outperform codes of the same length and rate. Recent commercial proposals demonstrate that polar codes with SCL decoding are capable of outperforming LDPC codes in short block lengths and low code rates without introducing any error floor. Furthermore, 1-bit granularity in polar codes is achievable for all coding rates and for the full range of block sizes, perfectly avoiding the

Table 2 A table of channel codes with some relative properties

	BCH	TB-CC	Turbo	LDPC	Polar
Performance approaching Shannon's limits	×	×	√	√	√
Good performance for short lengths	√	√	×	×	√
Capability to correct burst error	√	×	×	×	×
Maximum likelihood soft-decision decode	×	√	√	×	×
Decoding algorithms with low complexity	√	×	×	√	×
Bit-level granularity of code length	×	√	√	√	√
Floor-free	√	√	×	×	√

inflexibility of BCH codes. However, the implementation complexity of SCL increases with the list size, especially with larger block sizes [108], leaving the long processing latency to be still an unsolved issue. The important properties of aforementioned channel coding schemes are summarized in Table 2.

4.4 Flexible access control

Medium access control (MAC) protocols provide a mechanism for nodes to access the wireless medium in an efficient and collision-free manner. In a distributed network, the nodes share a common wireless channel by using the same RFs, in which case inappropriate use may lead to collisions and a waste of bandwidth. Hence, channel sharing is critical for guaranteeing high quality of service. Both low delay and high reliability are requisites to offer the operational effectiveness, while the mobility and geological scalability of nodes further impose difficulty for channel-sharing arrangements. MAC protocols are expected to satisfy such requirements and distribute the medium usage among different nodes by considering both fairness and efficiency.

The traditional MAC protocol for ad hoc network design generally does not make any restrictions on the antenna type, implying that the protocols enable the split of media by any appropriate method, such as time division, frequency division, and code division. Therefore, the nature of isotropic propagation of electromagnetic waves unavoidably results in collisions in medium sharing. Numerous schemes have been proposed to alleviate the collision issue. Although some of them are implemented under various design constraints and proved fruitful, the collisions still cannot be entirely mitigated. In addition, the existing ad hoc protocols can hardly adopt an appropriate medium-sharing scheme to meet the requirements of high mobility and frequent topology changes. On the other hand, with the recent development of directional antenna technology, the MAC protocol design based on directional transmission has drawn great attention. By utilizing the benefits of spatial division, it can achieve a higher network throughput and better jamming mitigation. Furthermore, the directional antennas transmit signals only in certain narrow azimuth, thus enabling the device to significantly reduce the chance of collision and increase the effective network capacity. The crucial drawback of directional antenna-based MAC protocols is that they highly rely on extra location tracking or relative navigation information, which can be unavailable or unreliable under certain circumstances, or even influenced by the high mobility. In this subsection, the existing protocols based on both omnidirectional and directional antennas are presented.

4.4.1 *Omnidirectional MAC protocols*

ALOHA is the world's first wireless packet broadcast system. Even today, the protocol is still popular in various applications [109]. The original mechanism (or "pure ALOHA") is quite simple: the transmitter sends a packet whenever it needs to, and it sends it again until an acknowledgement from the receiver is acquired. This scheme is preferred for its simplicity and scalability in truly decentralized networks. However, the protocol also has the downside: the network capacity obtained by the protocol is very low because any overlapping—even only partial overlapping—may cause packet loss. To address the collision issue, two major modifications are invented, i.e., time slotting and carrier sensing.

Slotted ALOHA (SA) introduces global synchronization and divides the channel into identical time slots, thus essentially avoiding the partially overlapping collisions. A more flexible variant called frame-

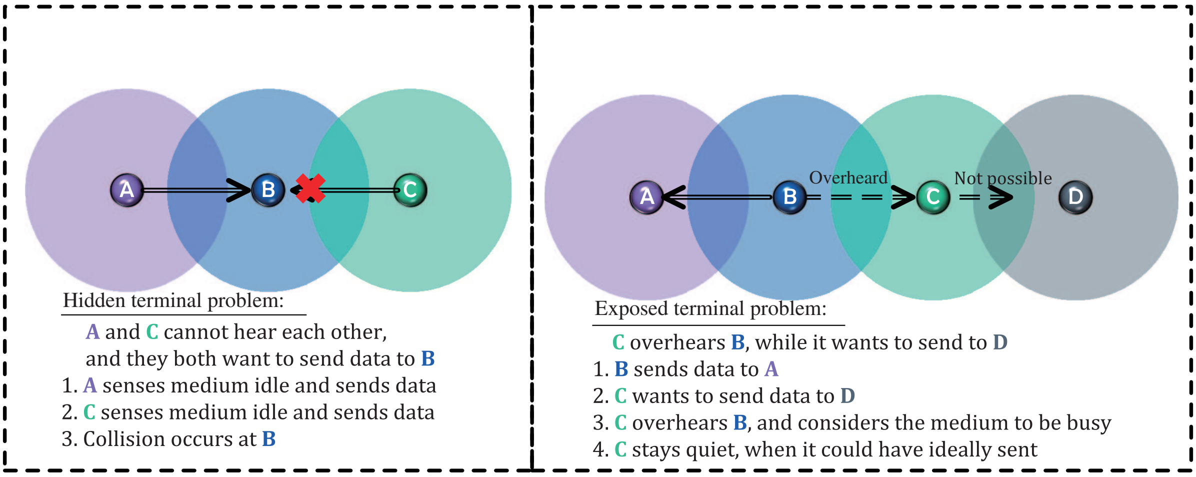

Figure 9 (Color online) The illustration and explanation of the hidden/exposed terminal problem.

slotted ALOHA (FSA) may be implemented for further dividing time slots into frames. In FSA, a user is allowed to transmit only a single packet per frame in a randomly chosen time slot. Owing to their effectiveness at tackling collisions in wireless networks, both SA- and FSA-based protocols have been applied extensively to various networked systems, ranging from satellite networks and wireless LANs to the emerging machine-to-machine (M2M) networks. The FSA has been recognized as a good alternative to handle the saturation traffic owing to its good performance when optimally configured [110].

In contrast, carrier-sense multiple access (CSMA) differs from ALOHA by sensing the channel occupation before attempting to transmit signals. Although much higher throughput can be achieved in CSMA compared to ALOHA, the former still encounters the famous hidden/exposed terminal problem [111], as illustrated in Figure 9. Many modifications have been suggested to overcome this inherent shortcoming. The CSMA with collision avoidance (CSMA/CA) protocol can efficiently reduce the collision probability by employing randomized backoff retransmission delay. In contrast, the multiple access collision avoidance (MACA) protocol uses positive handshake to confirm the channel, thus avoiding the hidden terminal problem. MACA for wireless (MACAW) protocol modifies this handshake by adding two control messages; however, this is at cost of an excessive transmission delay. Fortunately, the MACAW protocol has good control over congestion, and therefore it yields better throughput when the channel is noisy and crowded.

MAC protocols based on either ALOHA or CSMA generally operate very well in scenarios where the simultaneous transmissions rarely happen. However, most of the protocols rely on the backoff waiting mechanism to avoid collisions, thus failing to provide low delay performance under heavy-loaded networks.

To address the excessive delay issue, a promising strategy involves a collision-resolution algorithm (CRA), which resolves collisions by organizing the retransmission of colliding packets in a way that all packets are always successfully transmitted with finite delay. The basic CRA does not attain all the potential gains because it uses the same resources (slots) to transmit data and resolve contention [112]. Instead, it is possible to separate contention from data using contention-based access requests by employing mini-slots. The above concept becomes the foundation of the distributed queuing (DQ) protocol, which behaves as a random access scheme under low traffic and automatically switches to a reservation-based access scheme when the traffic load increases, thus obtaining low latency (for low loads) and scalable performance (for densely loaded networks) [113].

Distinguished from the aforementioned methods, which are designed mainly for commercial ad hoc networks, tactical data links have specialized MAC protocols with unique requirements. Most of the tactical data links employ spread spectrum-based protocols to enhance defense against detection and jamming. The statistical priority-based multiple access (SPMA) [114] method may be viewed as a generalization of CSMA for spread spectrum systems. SPMA employs a SFHSS modulation and corresponding coded

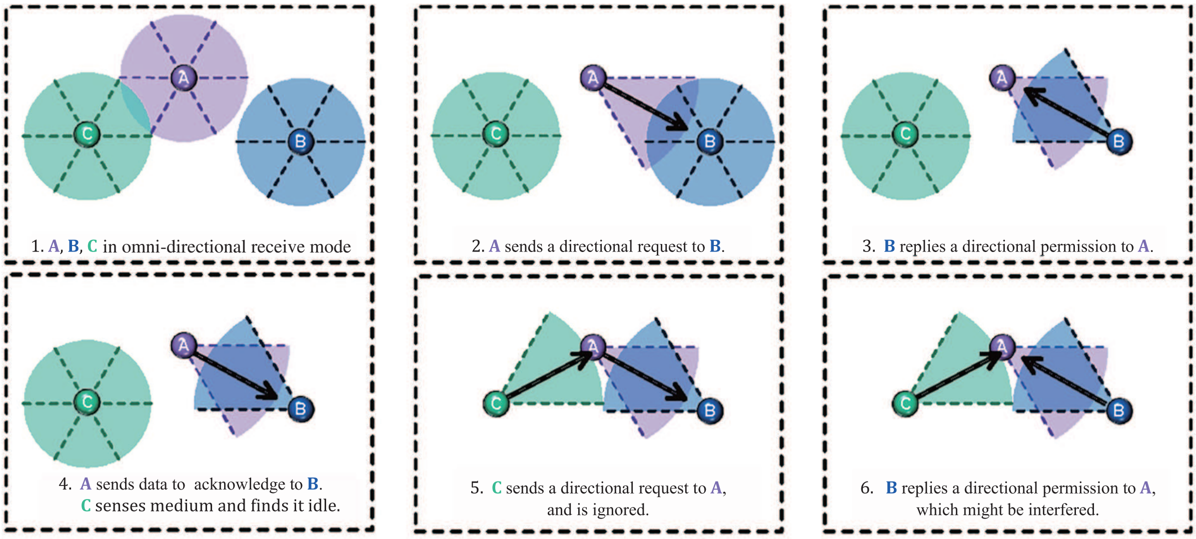

Figure 10 (Color online) The illustration and explanation of the deafness problem with directional MAC protocols.

division: the MAC protocol used by tactical targeting network technology (TTNT). While conventional CSMA uses a narrowband signalling channel that is either busy or idle, the spread spectrum channel of SPMA takes on many different states depending on the ongoing traffic. A node constantly senses channel occupancy statistics to automatically judge the probability of successful transmissions. When data packets arrive for transmission, they should be put into a queue according to their priority orders. The front packet of the queue is sent only when the chance of successful transmission is sufficiently high, or else it must wait for a random backoff before the system rechecks it.

As a self-organizing dynamic allocation protocol, SPMA can be improved in terms of power and bandwidth efficiency over classical ALOHA systems, and outperforms CSMA systems in terms of traffic successful ratio. However, those features heavily rely on several components [115], such as real-time generation of channel occupancy statistics and error correction coding methods with excellent erasure properties.

4.4.2 *Directional MAC protocols*

Directional antenna technology is currently gradually being introduced into ad hoc networks to improve channel utilization and network scalability. The directivity of transmission enables less interference between links, thus increasing the spatial reuse of the wireless channel. Because this technology can perform multiple simultaneous transmissions in the same vicinity, it is expected to significantly increase network capacity. The high gain of directional antennas extends single-hop transmission range, resulting in a decreased routing hop and consequently reducing the end-to-end delay [116].

As a concept commonly used in ad hoc networks, CSMA has received widespread attention, and many existing studies have been dedicated to solving CSMA-based directional MAC protocols. Despite the many benefits of this technology, deafness is known to occur with these protocols. Once deafness occurs when the transmitter attempts to communicate with the receiver, the communication may be owing to the antenna of the receiver pointing away from the transmitter, as demonstrated in Figure 10. The deafness problem may lead to short-term unfairness between flows that share a common receiver. Furthermore, a chain of deafness is also possible in which each node attempting to communicate with a deaf node becomes, itself, deaf to another node, resulting in a deadlock scenario.

The existing solutions to the deafness can be classified as four types.

(1) Using multiple control frames [117]. The approaches using multiple control frames try to solve the deafness problem by disclosing the transmission information to all the neighboring nodes. The nodes receiving the control frame are capable of cognising an upcoming communication and will delay their

packets to avoid deafness.

(2) Notifying potential senders [118]. Instead of transmitting control frames, the schemes based on notifying potential senders exploit a local table that maintains the potential senders who have previously transmitted an advance notice. The advance notice informs the receiver that the sender will transmit data in the next available time so that the sender can minimize deafness duration.

(3) Using busy tone [119]. In the busy tone-based solutions, both the sender and receiver omnidirectionally broadcast busy-tone signals in a segregated control channel to distinguish deafness from a collision.

(4) Splitting channel [120]. In splitting channel schemes, one logical channel is dedicated to filtering the data traffic and another to controlling packets, allowing nodes to recognize and mitigate efficiently the collisions that occur because of deafness.

Although those schemes are shown to be somewhat effective, none of them have comprehensively resolved the deafness issue [120,121]. In addition to deafness, the biggest problem for the implementation of directional MAC protocols is the requirement for location awareness. Note that the location information is the foundation of relative orientation and consequent beamforming. Most of the aforementioned protocols are developed for vehicle or sensor networks in which the nodes are generally equipped with global navigation satellite system (GNSS) terminals. Timely location information of nodes can be obtained and exchanged in the network. In contrast, UCAVs are designed with maximum autonomy, namely independence from external supporting systems, including the GNSS. Although the location information can also be obtained within the network system through relative navigation, it may be only feasible in a limited adjacent range.

Another critical issue comes from the extreme mobility of hypersonic UCAVs. The performance of carrier sensing-based protocols generally can be affected by factors such as node position, speed, direction of movement, potential communication duration, and the potential number of communicating neighbors, all of which are highly dynamic in inter-group communication networks and are difficult to predict owing to the extreme mobility [122]. In addition, for the directional MAC protocol, each node needs to maintain a table of location information, so the mobility of the node will inevitably cause a deviation between the cached information and the actual location. This gap deteriorates the reliability of the transmission, resulting in errors and failures. This situation can be alleviated through optimization of related parameters such as beamwidth, retry-limit, and lifetime of location information table [123].

4.5 Ad Hoc routing in extremely high mobility

The large geographic coverage of hypersonic UCAV operations dictates that the nodes cannot directly communicate with each other in an arbitrary manner. Relying on routing protocols, each node has the capability to find best path to deliver packets through the network. As such, the performance of routing protocols will ultimately affect the connectivity and efficiency of network.

There have been many routing protocols for wireless ad hoc networks, such as pre-computed routing, dynamic source routing, on-demand routing, cluster-based routing, and flooding. However, most existing protocols are not directly applicable here. Owing to the high mobility of hypersonic UCAVs, the network topology changes frequently for the protocols to maintain stability. In addition, low end-to-end latency requirements limit the discovery time and routing hops of affordable paths.

Corresponding to the flourishing development of UCAV networks, a number of alternative schemes have been proposed to address the rapid changes in ad hoc network topology. These protocols can be classified into four major categories: (1) reactive routing; (2) proactive routing; (3) cluster-based routing; and (4) directional antenna-based routing. The four types of routing protocols will be introduced in following, with their pros and cons compared in Table 3 [124]. Any breakthrough for all these protocols would require the location information and link state prediction into the path selection criterion to cope with the rapid topology changes.

Table 3 Advantages and disadvantages of routing protocols

Type	Protocol	Advantage	Disadvantage
Reactive	AODV	Adaptive to changing environments	Large delay after node or link failures
	RGR	Better delivery ratio and end-to-end delay	Packets lost if the geographic information become invalid under high mobility
Proactive	OLSR	Shortest hop forwarding path	Frequent interruption for rapid changing topology
	P-OLSR	Adaptive to highly dynamic networks	Difficult to recover after sudden disconnection
Cluster	See [124]	Avoidance of collisions	Heavy dependence on the connectivity of cluster head nodes
Directional	RARP	Using trajectory information to predict location information	Additional overhead to deliver movement vectors
	HSD-R	Reduced network load with reasonable short delay	Possible intra-sector collisions

4.5.1 *Reactive routing protocols*

In a reactive or on-demand protocol, when the source wants to send to the destination, it will necessarily call the route discovery mechanism to find a suitable path. In this sense, reactive routing is suitable for high mobility scenarios where the link state changes rapidly. However, even so, this mechanism causes large end-to-end delays owing to frequent path exploration.

The ad-hoc on-demand distance vector (AODV) protocol is a representative reactive routing that assigns dedicated time slots for packet transmission to avoid congestion and improve packet delivery ratio. In AODV, all source nodes only store the next-hop information. In the process of routing building, when the next hop is unreachable, two options are designed: dropping the packet, or resending the packet using the newly reestablished or repaired route. The hop-by-hop routing strategy gives AODV a great advantage in dynamically changing environments. Based on AODV, the reactive-greedy-reactive (RGR) protocol is proposed by assuming the nodes can obtain accurate location information and make mobility predictions [125]. By combining the advantages of reactive and geographic mechanisms, the protocol searches for the route with the smallest hop count and shortest transmitting range, providing significantly higher packet delivery ratios and lower end-to-end in high mobility and density-variable scenarios.

4.5.2 *Proactive routing protocols*

In a proactive or table-driven protocol, the routing information is recorded and stored in each node in advance. Following this mechanism, the packets can be sent immediately without a long path-exploring time. However, the disadvantage of the above mechanism is that when the network topology changes, this update information must be transmitted in the entire network in time to ensure that each node maintains the latest routing information in real time. Obviously, this will generate significant information sharing overhead.

The optimized link state routing (OLSR) protocol is a well-known proactive routing protocol in ad hoc networks that employs the periodic exchange of messages to maintain the topological information of the network at each node. By using multiple relay schemes instead of pure flooding, OLSR greatly reduces message overhead. However, OLSR takes several seconds to detect link breaks, which translates into frequent interruption of the communication for rapidly changing topologies. To solve this problem, an extension to the OLSR named predictive OLSR (P-OLSR) is presented by using the navigation information available on board to obtain the direction and the relative speed between nodes, which can be used to evaluate the link quality [126]. By always choosing the high-quality links, the routing follows the topology changes without interruptions.

4.5.3 *Cluster-based routing protocols*

Unlike the flat-based protocols (e.g., AODV, OLSR), where all nodes are treated equally and have same functionalities in network, the clustering is a type of hierarchical routing protocol. It divides nodes into different clusters according to their capabilities, mission arrangements, or geographic distribution. In each cluster, only the selected cluster head node is responsible for performing inter-cluster communication and relaying the traffic within its cluster. Compared with a flat topology, cluster topology is easier to manage and more scalable in respond to unscheduled events. By cluster division, the collisions are largely avoided, and accordingly, end-to-end delay is reduced [127]. An extensive survey on cluster-based routing protocols for unmanned aerial vehicle networks was presented recently [124], in which a handful of promising schemes [128, 129] for high mobility scenarios can be found.

The fundamental problem with implementing cluster-based routing is that it depends heavily on the connectivity of the cluster's head nodes, and owing to operational or geographic reasons, the connection is likely to be blocked, paralyzed, disrupted, or unreachable. When the cluster head is detected as unqualified to provide an efficient interconnection, the protocol invokes re-election or reorganization, which causes additional overhead and can result in interruption of network communication [130].

4.5.4 *Directional antenna-based routing*

The application of directional antennas can substantially increase the capability of wireless networks by eliminating the interference between concurrent transmissions from neighboring nodes [131]. However, most of the existing routing protocols are based on omni-antenna designs. Owing to the severe challenges of neighbor discovery and path stability, these protocols cannot be directly applied to directional antenna scenarios.

The robust and reliable predictive (RARP) routing protocol combines omnidirectional and directional transmission schemes together with dynamic angle adjustment [132]. It utilizes omnidirectional flooding for neighbor discovery. Prediction mechanisms are employed to determine the node location and its trajectory to enhance the routing efficiency and path stability. During the delivery of data packets, the directional antenna is used to increase the communication reliability. Furthermore, RARP requires source and intermediate nodes to piggyback their position and movement vectors onto each data packet to maintain the freshness of geographic information tables, which degrades transmission efficiency and increases end-to-end delay.

The history-based section distribution routing (HSD-R) protocol is purely directional [133], which means its neighbor discovery and packets routings are all finished by directional antennas. In the neighbor discovery stage, a node turns its directional antenna to exchange location information with neighboring nodes in different sectors as much as possible. The antenna-turning arrangement is based on an algorithm called history-based sector distribution, which enables the nodes to sense topological changes around them. According to the information collected during the neighbor discovery stage, a routing protocol based on the conventional epidemic routing protocol is performed and effectively reduces the load of network with reasonably short delay. However, the possible intra-sector collisions in neighbor discovery are beyond the scope of this study.

5 Open research issues

As previously described, there are several unique requirements in the UCAV swarm design, and low end-to-end delay in highly dynamic conditions is the most challenging. In Section 4, state of art in technologies is introduced, including antenna arrays, spread spectrum, channel coding, MAC protocols, and routing protocols. Although many of these technologies are promising, there are still open issues awaiting further research.

Millimeter-wave antenna arrays benefit from substantial bandwidth and relatively small physical size. But on the downside, the accuracy phase modulation at the millimeter-wave band is difficult to achieve with the I/Q imbalance problem [134].

DS/FFH hybrid spread spectrum schemes have great advantages in communication reliability and security. However, the acquisition efficiency of DS/FFH-HSS may become a bottleneck in system performance. Evidently, fast acquisition of DS/FFH-HSS in harsh environment and high mobility with limited on-board processing resources has constituted an extremely challenging issue.

Polar codes with SCL decoding are an outstanding channel coding scheme with 1-bit granularity and no error floor. However, the implementation complexity of SCL increases with the list size, especially with larger block sizes [108], leaving the long processing latency remain an unsolved issue.

Directional MAC protocols have good performance, but most of them require for location awareness, which is possibly unavailable in UCAVs. In addition, the extreme mobility of hypersonic UCAVs brings deterioration to transmission reliability, resulting in errors and failures. This problem requires further research on parameter optimization.

Similarly, the directional antenna-based routing protocols suffer from rapid location information staleness owing to the high mobility of hypersonic UCAVs.

6 Conclusion

The hypersonic UCAV swarm provides rewarding and long-desired tactical utility. It can carry out missions such as saturation attacks, situational awareness sharing, distributed cooperative guidance, cooperative path planning, cooperative searching, and eventually, the cooperative autonomy. The foundation of the sophisticated coordination is inter-group communication, which is envisioned to be provided by a specialized wireless network. In this article, the network for hypersonic UCAV swarms was defined as a highly dedicated ad hoc network that can be adaptive to high mobility, dynamic topology, large geographic coverage, and hostile environments, as well as capable of supporting various services with low end-to-end delay and high reliability. The main technical challenges in designing hypersonic UCAV swarm include antenna design, spread spectrum modulation selection, channel code design, and MAC/routing protocols optimization. In this article, we presented a comprehensive survey on the state-of-the-art technologies, followed by comparing various schemes in terms of performance. Furthermore, we highlighted the potential solutions and identified the challenging issues for future studies.

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