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Health Monitoring Based on Internet of Medical Things: Architecture, Enabling Technologies, and Applications

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ABSTRACT Recently, wearable devices have got increasing popularity in wide applications in medical and disaster rescue efforts to ensure the health and safety of users, which facilitates the development of the Internet of Medical Things (IoMT). Due to the posture alteration and mobility of users, the topology of the IoMT changes frequently, which increases the difficulty for resource allocation and routing strategy. In this paper, we respectively probe into the health monitoring architectures of the IoMT for both individual and group, allowing the monitored users to move at will. Furtherly, combined with the diversity of disaster rescuers, we build an IoMT-based disaster rescuer health monitoring system with searchers, doctors and porters. For each application, we point out the enabling technologies and demonstrate the existing researches. It is worth noting that the complexity of environment and high mobility of rescuers increase the probability of route breakage. Thus, this paper creatively addresses effective routing repair solutions for route breakage in IoMT-based disaster rescuer health monitoring system by exploiting the mobility of rescuers. Finally, we forecast three most likely directions in the field of IoMTs.

INDEX TERMS IoMT, health monitoring, individual, group, disaster rescuer.

I. INTRODUCTION

With continuous development of microelectronics, communication technology, and sensor technology in recent years, portable and intelligent wearable devices have become increasingly popular in various countries around the world [1]–[3]. As the name suggests, wearable devices mean that the devices people can wear on their body in forms as necklaces, belts, watches, etc. Wearable devices have built-in sensors with independent computing power and dedicated functions, so they can monitor physiological information including heartbeat, blood pressure and breathing, etc., and body movement such as speed, posture, direction and position. Such devices can also monitor the environment, including temperature, humidity, and air quality, etc. Wearable devices can also connect to smart phones, tablets, computers, and other devices through technologies like Bluetooth, WiFi, and ZigBee [4], [5]. As such, they are widely used in medical care, sports, and fitness to monitoring the human health [6]–[9]. As wearable technology matures and upgrades, the IoMT shapes gradually with the key technologies of Physiological information perception and remote data transmission [10], [11].

Recently, more kinds of diseases threaten the people's life, individual health monitoring becomes significant not only for the patients but also the aged and the healthy persons with potential health risk. The occurrence of the IoMT provide incomparable changes for healthcare. The people equipped with wearable devices can monitor their health signals continuously and transmit them to the gateway within 3-6 meters [12], [13]. Through the connection between the gateway and external network, the IoMT realizes the remote

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transmission to the doctors or family by the aid of 5G or fiber networks (i.e., passive optical network (PON)).

The development of human-centric Internet of Things (IoT) [14]–[19] and social network [20]–[22] reveal the fact that modern society pays more and more attention to the connection among people. This phenomenon is also open a new research field for health monitoring. Thus, group health monitoring based on the IoMT is reasonable to promote the healthcare level. In this case, multiple users can form a multi-hop self-organized network which allows the users moving in a larger area and consume less energy.

Meanwhile, the rate of man-made and natural disasters is increasing worldwide [23], disaster rescuers face various uncertainties and potentially fatal dangers including low visibility, very high ambient temperature, and emission of toxic gases. Thus, health monitoring for the rescuers is very important but is neglected. The IoMT can be used in disaster rescue to monitor the health of rescuers to reduce life damage. However, due to the mobility of users and the complexity of the environment [24], the route paths face frequent changing topology and many breakages. Thus, it is important to study the routing selection scheme and repair scheme to ensure the smooth communication.

In this paper, we discuss the applications of the IoMT on popular health monitoring for individuals and group in daily, respectively and especially exploit an architecture for the IoMT used in disaster rescuer health monitoring with consideration of distinct roles. The most important contribution of this paper is that we address routing repair schemes for the proposed architecture, which is never touched in the previous literatures to our best knowledge. In the following sections, the paper is organized as follows: In Section 2, we first describe the architecture, the key enabling technologies, and the current research status of the individual health monitoring system. In Section 3, we explore the architecture of the group health monitoring system on basis of the application in industrial workplace. Then we point out the backbone technologies according to the inter-human unique attributes. Finally, we show the up-to-date researches of the group health monitoring system. In Section 4, oriented to the emergency scenario of disaster rescue, we devise the specific health monitoring architecture based on the IoMT. Then the critical technologies to solve the particular routing problems is presented and the existing studies are demonstrated. In Section 5, challenges and future research directions are discussed for the IoMT development in health monitoring and other prospective wider application. We conclude our work in Section 6.

II. IoMT-BASED INDIVIDUAL HEALTH MONITORING SYSTEM

Based on the wearable technology, the IoMT is always used for the individual health monitoring in daily life. In this section, we introduce the architecture of the individual health monitoring system, discuss the related enabling technologies and introduce the existing researches on energy-saving for individual health monitoring system.

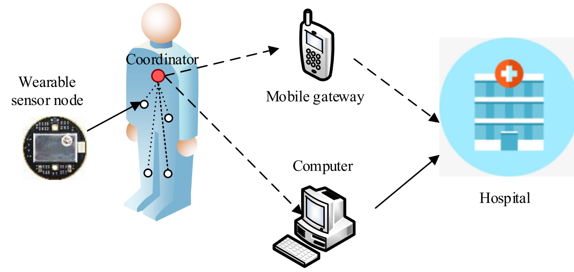

FIGURE 1. The architecture of IoMT-based individual health monitoring system.

A. ARCHITECTURE OF IoMT-BASED INDIVIDUAL HEALTH MONITORING SYSTEM

Due to the rapid development of wearable devices, the IoMT has become the most commonly used technology for health monitoring [25]–[27]. In traditional health monitoring, the patients always connect to the computer through wired monitoring terminals. The biggest disadvantage is that the patients cannot move at will. In fact, staying in bed for a long time is bad for health. The IoMT has solved this problem. The architecture of IoMT-based individual health monitoring system is shown as Fig. 1. The sensors on body can monitoring the health signals such as blood pressure, heartbeat and others. The coordinator on human body takes charge of the connection to the family and the doctor through the Internet. Compared with traditional health monitoring, the IoMT-based individual health monitoring system can increase the lifetime of nodes because the nodes on human body can form a network and perform energy-saving technologies.

B. TECHNOLOGIES OF IoMT-BASED INDIVIDUAL HEALTH MONITORING SYSTEM

With the increasing date volume, some key technologies of IoMT-based individual health monitoring system are important.

1) MARKOV MODEL

Markov model is often used to describe the stationary stochastic process. In individual health monitoring system based on the IoMT, the common postures for users are standing, sitting, laying, walking, and running which can be described by Markov model. There is a probability from a posture state to another one. The work in Ref. [29] presented a Markov model for postures, just as shown in Fig. 2. Liu *et al.* divided the walking process into three posture states and designed a Markov model for them, just as shown in Fig. 3, where M(0), M(1) and M(2) represent the three posture states respectively [30].

Markov model is also widely used in the IoMT for other aspects. The work in Ref. [31] took constrained Markov decision process into the dynamically sensors scheduling for channel use. Discrete time Markov chain method is

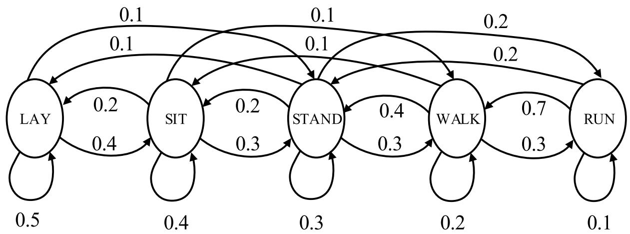

FIGURE 2. Markov model for five states transition diagram.

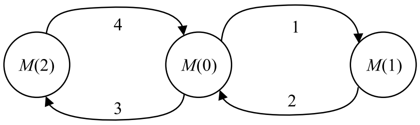

FIGURE 3. Markov model for three states transition diagram.

used to compute the access probability of every sensor [32]. Yang *et al.* captured the dynamic channel behavior and concluded six states, then they designed a Semi-Markov model contain the situations in Line of Sight (LOS) and Non Line of Sight (NLOS) [33].

2) MOBILITY MODEL

One of the biggest virtues of IoMT-based individual health monitoring system is that the devices do not restrict the human activities, i.e., the users can walk at will. However, the motion mode can affect the network performance at a large extent. Currently, some researchers studied the mobility model in the IoMT. The work in Ref. [34] presented an average mobility in hospital room, and considered two scenarios of standing and walking. The mobility model in Ref. [35] allows the user to choose a random room, walk to the room in a random speed and stay for some time after reaching to the selected room. The work in [36] revealed that it is difficult to predict where the patients want to go. Thus, the authors restricted the range of patients' activity on one floor and then used a nomadic mobility model.

C. APPLICAITIONS OF IoMT-BASED INDIVIDUAL HEALTH MONITORING SYSTEM

Energy saving is one of the major negative factors for the IoMT development. How to reduce the energy consumption and increase the network lifetime is a tough challenge in routing protocols and Medium Access Control (MAC) protocols.

1) ROUTING PROTOCOLS

Mainstream routing protocols in ordinary WSNs were analyzed and improved to match the IoMT [37], [38]. An energy-efficient routing structure based on uniform clustering algorithms was proposed to solve the survival time of the IoMT [39]. This method is superior to the existing wireless somatosensory network scheme in the aspect of energy consumption and network lifetime. Another study proposed an adaptive greedy buffer allocation and scheduling algorithm [40]. This algorithm produces more residual energy and lifetime at the node compared to the traditional routing algorithm, meaning the sensor can last for a longer period of time, especially under special circumstances such as in mines, tunnels, and holes. A cost-based energy efficiency routing protocol was designed in [41] which ensured that the sensor does not have thermal effects while providing satisfactory performance. This method can be applied to most interference conditions and enhance the energy efficiency of the wearable devices. Ababneh *et al.* proposed an energy-balanced rate allocation and routing protocol to improve the performance in terms of energy balance, network utility and lifetime [42]. In this protocol, the data is transmitted intelligently according to a designed utility, and the data rate of each nodes is selected by link utilization to avoid heavy load.

2) MAC PROTOCOLS

To promote Quality of Service (QoS) of the IoMT on user level, data level and time level, a multi-level MAC protocol was proposed [43]. The QoS can be improved by differ the priorities for users and data. The proposed solution can provide good performance on QoS and energy saving. Based on IEEE 802.15.4, Khan et al. proposed a new MAC protocol to solve the energy and emergency data problems [44]. For different kinds of data, they used different solutions. For emergency data, they used an emergency beacon message to reduce the transmission delay. For periodic data, they used fixed bandwidth allocation. For normal data, they used slotted CSMA/CA mechanism. Similarly, based on IEEE 802.15.6, Yuan *et al.* proposed a new MAC protocol by distinguishing the traffic types and user priority to cut down the energy consumption of nodes and prolong the network lifetime [45].

III. IoMT-BASED GROUP HEALTH MONITORING SYSTEM

Recently, the issues of human behavior monitoring and interacting with the surrounding environment have become the promising researches [46]. Based on the IoMT, the group health monitoring system is the updated version of individual health monitoring system, allowing the inter-human communications. To be specific, the individuals in group health monitoring system can forward the data of other individuals. Thus, multiple individuals form a multi-hops network.

The sensors on an individual can interfere that on other individuals if they are closely. To reduce the interference in channel, Alam et al. proposed three coexistence strategies based on time-shared, channel hopping, and CSMA/CA technologies respectively [47]. If there are large amount of individuals in a network, the network throughput is also a problem to solve. To provide high efficiency and reliability for date transfer with high throughput, Shimly *et al.* proposed a cross-layer carrier sensing scheme to pass the channel state information from physical layer to the network layer [48]. As many users in the network moves freely, the stable and reliable routing is a tough challenge. The problem is that there are no specific route standards for the IoMT. Thus, the study up-to-date trends to evaluate the existing universal routing

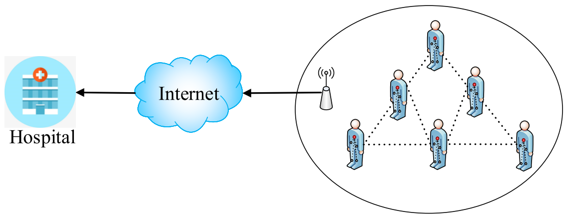

FIGURE 4. The architecture of IoMT-based group health monitoring system.

protocols just like the hybrid adaptive routing protocol in similar mobile Ad hoc network [49], and then add human mobility characteristics into these protocols. In this section, we first describe the IoMT-based group health monitoring system and then introduce the enabling technologies and the existing research actuality.

A. ARCHITECTURE OF IoMT-BASED GROUP HEALTH MONITORING SYSTEM

Different from the short distance communication on human body, the group health monitoring system mainly emphasizes on the information transmission between individuals. If we view the connections on each individual as a whole, the group health monitoring system is similar to the opportunistic network and can be structured in centralized, distributed, and clustered way. In centralized structure, the coordinator on a given individual is the center of all other individuals and takes charge for their data gathering and transferring. In distributed structure, all the individuals communicate with others in a self-organized way through their own coordinator. In clustered structure, several individuals join into a cluster and select an individual as cluster head, then the coordinator in the head individual is responsible for the connection with other clusters. Considering the rapid development for Internet of Human (IoH) and IoT, the group health monitoring system has great potential to be applied in future healthcare. Based on the architecture of the group system proposed for industrial workplace application [51], we propose a feasible architecture of IoMT-based group health monitoring system, taking the distributed cluster as an example, just as shown in Fig. 4. All the individuals can transport their data collected by the sensors on the body to the access point through multi-hop transmission. The access point takes charge of the transmission to the remote nodes such as the monitoring terminals in hospital.

B. TECHNOLOGIES OF ARCHITECTURE OF IoMT-BASED GROUP HEALTH MONITORING SYSTEM

To facilitate this proposed system, it is necessary to use some key technologies.

1) MOBILITY MODEL

In the IoMT-based group health monitoring system, the user mobility models impact on the inter-user route deeply, which can be divided into entity mobility model and group mobility model. The most frequently used entity mobility models including random waypoint model [52], random walk model [53], random direction model [54], and Gauss-Markov mobility model [55], etc. Reference point group mobility model, column mobility model and pursue mobility mode [56] are the group mobility models. Liu *et al.* analyzed the existing mobility models and revealed that Gauss-Markov mobility model is the most similar with the human movement [30]. However, Gauss-Markov mobility model is an entity mobility model, which cannot present the characteristics of the IoMT with multiple nodes. Therefore, they built a new Gauss-Markov mobility model with three-dimensional motion model of key nodes of human body. This new model can better describe the walking process of human.

2) COOPERATIVE COMMUNICATION TECHNIQUES

Cooperation is a helpful method to realize the network performance [57]. Especially, Cooperative communication is a common technique always used to mitigate interference in wireless network. It allows that two or more nodes cooperatively built a virtual antenna array for mutual communication, which reduces the transmission power and increases the capacity for the specific node by spatial diversity technique. In crowded environment with multiple individuals, the channel interference will degrade the performance and utility of the IoMT [58]. Some researchers have studied the application of cooperative communication in the IoMT for interference mitigation. For overlapping superframes and high probability of channel sharing, Ali *et al.* proposed a distributed orthogonal code allocation scheme and a time reference correlation scheme [59]. To settle the data transmission interruption, Manirabona *et al.* proposed a routing protocol by considering three cooperative communication scenarios: 1) between two coordinators; 2) between coordinator and node; and 3) between node and node [60]. Dong *et al.* proposed a two-hop relay-assisted cooperative communication to enhance the coexistence of individuals and reduce the interference [61].

3) GAME THEORY

In wireless network, multiple users compete with each other for the limited spectrum and channel resource, which inevitably causes the interference among users. During the competition process, the high utility is the main goal of all users. Thus, game theory is a good solution for resource allocation and channel sharing [62]. To mitigate the socially-aware interference, Liu *et al.* proposed a game theoretical method with two-stage channel allocation scheme including the game for allocating WiFi channels among individuals and the game for allocating ZigBee channels for nodes on the human body [63]. Kazemi *et al.* revealed that interference has bad effect on reliability and power consumption of individuals. Taking inter-human interference between closely individuals into consider, they addressed a non-cooperative power control game by using pricing mechanism [64]. To enhance the network capacity and mitigate the interference, Wang *et al.* presented a cooperative Nash bargaining game for inter-human and a Stacklberg game for the network on each human body [65].

C. APPLICATIONS OF IoMT-BASED GROUP HEALTH MONITORING SYSTEM

The energy consumption of IoMT-based group health monitoring system is also a limited consideration for its development. In the following, we investigate the existing researches for the IoMT-based group health monitoring system from the aspects of routing protocol and MAC scheduling algorithm.

1) ROUTING PROTOCOL

The broadcast characteristics of information channels in the IoMT were studied in [66], and an opportunistic routing protocol on basis of random linear network coding was proposed. This protocol uses a distance-unstable chain which is unavailable in traditional routing protocols and has achieved significant improvements in network throughput and end-to-end latency. The design of the IoMT monitoring system was presented along with an improved classic acquisition tree protocol as well as a routing protocol based on fuzzy logic routing algorithm in the Ref. [67]. This sensor node can transmit data in real time with high reliability and balanced node energy consumption, making practical use of network resources and extending network endurance. Finally, the work in Ref. [68] presented a low-power and low-loss network routing protocol design based on the new energy-aware objective function to improve network lifetime. And to optimize the path for route packets through the network, the expected transmission count and the remaining energy of nodes are used in the proposed objective function. Meharouech et al. designed an IoMT-based Epidemic control architecture and then proposed a location-aided routing protocol which contains the considerations of QoS, mobility of users and energy efficiency [69].

2) MAC SCHEDULING

Technically, resource scheduling on MAC level is an excellent method to enable the IoMT-based group health monitoring system more effective and energy-efficient. Fan *et al.* concluded the scheduling problem between individuals into a graph coloring problem between coordinators, and then proposed a heuristic hybrid simulated annealing algorithm to optimize the performance of the network [70]. Yi et al. focused on the scheduling problem of packets with different priorities in e-health network by using the multi-level multi-server queueing model [71]. To allocate resource for both inter-human and each individual, Huang *et al.* developed a two-step allocation protocol based on weighted random value system which considers the requirement of urgent signals [72]. First, coordinators in nearby individuals negotiate the resource allocation between them and then the coordinator with allocated resource takes charge for scheduling within its individual.

IV. IoMT-BASED DISASTER RESCUER HEALTH MONITORING SYSTEM

As we all known, communication among rescuers is extremely important during emergencies. The control center publishes key information to the rescue team, including weather conditions, navigation maps, the nature and conditions of the disaster, and safety-related information such as safety zones. The control center then coordinates and broadcasts the responds from the rescue teams. Therefore, maintaining communication is the foundation for successful rescues. Numerous scholars have proposed plans for maintaining communication in rescues. In [73], an inter-human architecture framework was introduced, and is an add-on to existing PSN infrastructure. In [74], researchers achieved safe evacuation in an earthquake by modeling the road network traffic (RNT) using data communication network (DCN). The work in Ref. [61] applied the Delay Tolerant Networks (DTN) into the disaster area where the infrastructure was damaged, and built an energy-aware communication network using existing mobile platforms, namely, mobile phones. Additionally, they proposed a prediction-based routing and transmission control scheme to enhance the performance of the geographic routing protocol. Based on the assumption that Mobile Ad-hoc NETworks (MANETs) can adapt to an emergency rescue scenario, the work in Ref. [75] proposed an active routing protocol which aims to maximize the node lifetime and quickly adapt to changes in the network topology. The work in Ref. [76] proposed a multi-level assignment model for a rescue team to respond dynamically to disasters. Based on the cost-benefit coordination principle, it also proposed three priority scheduling strategies which were verified as superior to other strategies. However, the strategy selection must be based on the maximum allowed rescue time.

Some scholars believed that Ad hoc networks are suitable for emergency rescue scenarios. A disaster response supported Ad hoc wireless architecture was built to minimize network congestion through novel topology management schemes and multi-channel radio protocols [77]. However, this approach leads to positioning inaccuracy, network sparsity and inefficient multi-hop algorithms, especially for indoor rescue operations. The work in Ref. [78] proposed a new QoS-based on-demand cross-layer routing protocol based on Ad hoc network in disaster relief environments, and a new routing selection model for distributed channel allocation in dynamic spectrum access environments. The protocol fully considers primary user (PU) sensing, distributed spectrum allocation, MAC layer technology, and end-to-end QoS requirements. The work in Ref. [79] analyzed and evaluated routing protocols in the disaster area network from the perspective of the network layer to help researchers determine the content of study, selection of protocols, and trade-off factors. To adapt to the highly dynamic topology of emergency MANETs, the work in Ref. [49] proposed a hybrid adaptive routing protocol which adaptively alters

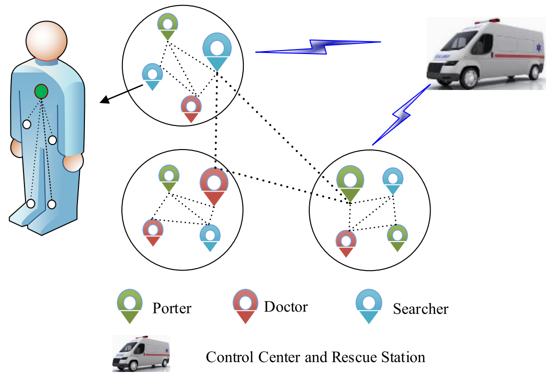

FIGURE 5. **The architecture of IoMT-based disaster rescuer health monitoring system.**

routing paths and provides an effective routing strategy for networks with different scales.

Identical to the abovementioned network, the IoMT also plays an important role in emergency rescue and the development of existing public safety networks (PSN) [80]. The work in Ref. [81] provided an overview of emergency rescue projects using the IoMT, related research challenges and objectives. This project was designed to provide ubiquitous wireless communication and monitoring systems for emergency relief to reduce casualties. The work in Ref. [82] focused on the IoMT challenges when applied to rescue and emergency situations. The study analyzed existing standards, elaborated on the need for multi-standard compatible devices, and reviewed the multi-standards of device-to-device communication based on wearable wireless cognitive systems.

In this section, we propose a new architecture of IoMT-based disaster rescuer health monitoring system, and analyze the enabling technologies and the existing research on this field.

A. ARCHITECTURE OF IoMT-BASED DISASTER RESCUER HEALTH MONITORING SYSTEM

In practical disaster rescue situations, searchers, doctors, and porter are three typical types of rescuers to be potentially equipped with wearable devices. Thus, an IoMT for monitoring the health of rescuers has been formed. The IoMT-based sysytem can monitor various human physiological information in real time and transmit the data through a self-organized multi-hop technique, making it suitable for ensuring the safety of rescuers in emergency situations. The architecture of IoMT-based disaster rescuer health monitoring system is illustrated in Fig. 5. In the proposed system, the nearby individuals will join into the same cluster and one of them is selected as the cluster head who is responsible for inter-cluster communication. All the collected information from individuals should be sent to the control center by off-body network through 4G/5G, WiFi, or satellites.

In the proposed network, disaster rescuers perform different tasks which enable them moving in different ways. The movement speed, direction, dwell time and trajectory may vary among the rescuers. For example, the searchers often access random places to search for victims, then they will notify medical personnel when they find someone. The doctors will receive the location information and go there. Porters follow the direction of searchers and doctors to reach the places where there are the victims and then take them to a specified safe area. What's more, due to different tasks, the rescuers may stand, walk, run, bow down, go prone, and posture other ways. For example, the usual postures for doctor is standing, run, and bow. Due to hold a stretcher together, two porters always do the same posture at the same time including standing, bow, and run.

B. TECHNOLOGIES OF IoMT-BASED DISASTER RESCUER HEALTH MONITORING SYSTEM

The varying movements of rescuers can create changing network topology, and bring significant challenges to the routing selection and routing repair. In the following, we first analyze the existing mobility models used in disaster rescue situations, then propose the routing repair solutions.

1) MOBILITY MODELS

Some researchers have presented mobility models used in disaster rescue situations. Based on the existing random mobility models, the work in Ref. [83] proposed a new random mobility model including all random attributes. For rescue and emergency applications of the IoH, the work in Ref. [84] respectively proposed a bio-mechanical mobility models for the body motion and a group mobility model for the IoMT. However, both of these two papers did not consider different kinds of rescuers, so did not provide specific mobility model for each kind of rescuers. The work in Ref. [85], [86] believed that not all rescuers move randomly, so the human behavior characteristics should be added into mobility models. In disaster rescue situations, the rescuers with the same tasks always have some same activities. For example, cruisers run to and fro on the main streets, and porters run between the rescue station and disaster area [87]. The concept for mobility of rescuers is similar to our proposed network model. However, it did not consider the postures of rescuers. Apart from run, the porters always bend down to carry the stretcher, and the doctor always bend down or squat to treat the injuries. And each action may last for some time. Thus, the postures of rescuers should be considered into the mobility model.

2) ROUTING REPAIR SCHEMES

In disaster rescue situation, there are many frequent disturbances such as high temperature and high pressure, fires, and heavy fog, etc. These disturbances combined with the constant movement of rescuers, are likely to cause link breakage and sensor node energy exhaustion in the network. In addition, a chaotic disaster relief site will often experience unexpected situations such as collisions between people and falling objects, increasing the probability of node failure. In order to maximize the rescuers safety, the disaster relief site has high requirements for network delay and rapid response sensitivity after failure. The repair scheme for the IoMT in disaster rescue is therefore particularly important, yet faces numerous unresolved issues and research gaps. We propose some solutions for routing repair as follows.

The route breakages may be caused by node failure or link breakage. Node failures in the IoMT include terminal sensor node failures, relay node failures, and coordinator failures. Link breakages may happen intra-cluster or inter-cluster [88]. To different kinds of failures, we need to uses specific routing repair method.

Based on the findings of previous research on node failure location, the damage of end nodes in a network is not considered as the main issue as it has little impact on the network's overall performance.

- For relay nodes on the individual

Damaged relay nodes affect the transmission of the entire route, which is considered as a main issue. Therefore, to reduce the impact of node damage on original data transmission, we propose a local routing repair scheme. When the data fails to be transmitted to the next hop node, a routing recovery scheme is initialized. This method will minimize the network topology changes when optimizing the route, which has the minimum impact on the original data transmission of the entire network.

- For coordinator on the individual

The coordinator on the individual is the center of other nodes on the body for coordinating and computing. When a coordinator is damaged or its energy is exhausted, we name it as failed coordinator which produces a high degree of impact to its belonged individual. In this case, the cooperative communication is needed to find another available coordinator in other individuals as substitute. The coordinators with higher remaining energy and closer to the failed coordinator are good candidates. As individuals move, the substitute coordinator may change to another one because of long distance or low energy. Thus, an adaptive cooperative communication algorithm is important to select suitable substitute coordinator along with varying topology.

- For cluster head node on the individual

The cluster head node is the core of the member nodes in a cluster and will need replacement if it fails. The cluster head generally has large energy consumption due to its large capacity, so the new cluster head requires frequent upgrades when it exhibits low energy. A dynamic cluster head node selection threshold can be used by considering the factors of network real-time load, node residual energy, and node motion trend, etc. When the new cluster head is in low-power state, the cluster head rotation scheme is initiated. This scheme is beneficial for improving the lifetime of the nodes, preventing early death for nodes, and prolonging the lifetime of the network.

- For link breakage in a single cluster

Rescuer movement and the hazardous disaster relief environment often lead to the breakage of communication links. Link breakage usually happens when the rescuer moves quickly or the signal channel is disturbed. To avoid the reoccurrence of link breakage after repair, a reliable route recovery algorithm should be designed to search for reliable and stable routing paths based on link stability which is related to data urgency, user behavior prediction results, and network delay, overhead, node residual energy, node busy rate, and link stability.

- For link breakage between clusters

The communication link between clusters may be broken by the complex environment of the disaster relief site and an accident. In this situation, the control center may not be able to accurately obtain the physical condition of the rescuers and the surrounding environmental information. In our proposed architecture, each cluster head is selected due to low mobility. A backup route can then be mounted between the cluster head nodes which will start immediately once an inter-cluster link fails. To improve transmission reliability and response sensitivity, energy balance, low latency, and link stability are main consideration.

C. APPLICATIONS OF IoMT-BASED DISASTER RESCUER HEALTH MONITORING SYSTEM

The network performance is crucial important for the IoMT-based disaster rescuer health monitoring system. In order to optimize the network throughput and QoS of IoMTs, a network management cost minimization framework was presented [89]. This work attempts to minimize the costs of dynamic link, interference management, and data dissemination to improve the IoMT network performance. The routing algorithms is also a usual way to promote the network performance. To improve routing performance in disaster relief, a wireless inter-human routing protocol named Optimized Routing Approach for Critical and Emergency Networks (ORACE-Net) was proposed [90]. In this work, Arbia *et al.* set up a mobile dynamic communication backbone network by fully using dynamic inter-human communication and maintained it. The work in Ref. [91] put forward a new priority queuing algorithm in Ad hoc On-demand Distance Vector (AODV) routing protocol which sorts different traffic flows based on key data to ensure that important information has high priority. The work in Ref. [92] proposed a multi-hop routing protocol in which transmission power, packet transmission rate, and network lifetime is enhanced. This protocol can maximize the network life and increase the transmission speed of data packets.

V. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

In previous sections, we have introduced the IoMT and its application in health monitoring. For health monitoring systems based on the IoMT, we have analyzed the enabling technologies and discussed the existing studies from the aspects of MAC level and route level. However, there are still some key technologies related to the IoMT in health monitoring not be mentioned. With the development of the IoMT, these unmentioned technologies will create great influence on human life and still be challenges and open issues for future IoMTs. In this section, we discuss the promising technologies used in health monitoring.

A. CLOUD COMPUTING AND FOG COMPUTING

The nodes in the IoMT continuously sensing, collecting and transmitting the signal data of monitored users results in massive data. Thus, an architecture enabling secure storage, powerful processing and scalable topology is needed in health monitoring [93]. As the third revolution of Internet, cloud computing is a good choice for the mentioned issues [94]. Some studies proposed cloud-assisted IoMTs to reduce the node energy consumption and transmission delay [95]–[97]. However, these studies did not take the communication and relationship inter-human under the proposed cloud-assisted IoMTs framework. Unlike cloud computing, fog computing is much closer to the users in IoMTs and can improve throughout and decrease the delay [98]–[100]. Both cloud-assisted and fog-assisted IoMTs in health monitoring are in the early stage while the energy-efficient and delay-aware mechanisms need to be developed deeply. In addition, hot technologies such as edge computing [101]–[105], network coding [106] and hierarchical technique [107] can also be used in our IoMT-based applications.

B. SECURITY

For purposes of privacy, the health signal data is not allowed to be leaked and disseminated. However, security issues always occur during the process of authentication and access control, especially in the IoMT with frequency interaction between users. Current investigations mainly focus on architecture construction and routing or MAC protocols to address the energy problem [108], [109]. Several research teams studied the security while still mainly focused on the network on the individual [110], [111]. Due to the growing complexity of the data and structure and the advancing network attacks with the times, the security problem is a significant and continuous challenge for IoMTs.

C. HETERGENEOUS NETWORK INTEGRATION

Because of the diversity of network forms such as Internet of Vehicle (IoV) [112]–[114], 5G [115]–[117], and other technologies, the integration of heterogeneous networks is an inevitable trend in future. Due to the requirement of human-oriented social development, IoMTs will be a general framework to combine with other advanced networks. The IoMT-based health monitoring system has been studied in some literatures [118]–[124]. However, other combinations with IoMTs are few.

VI. CONCLUSION

In this survey, we discussed the emerging IoMT and locked its application on health monitoring. We discussed and proposed the IoMT-based health monitoring systems for individual, group and disaster rescuers respectively. Specifically, for each system, we first introduced the IoMT-based architecture, then analyzed the key technologies such as Markov model, mobility model, game theory, etc., and finally studied the energy saving problem. The systems for group and disaster rescuers are based on the system for individual, i.e., they focused on the connections among individuals. Especially, the system for disaster rescuers took the social attributes of individuals and payed more attention to the routing repair. In the end, we predicted the future research direction of the IoMT including the combination with emerging technologies, network security, and heterogeneous network integration.

REFERENCES

[1] H. Yi, S. Lee, D. Lee, W.-G. Bae, T.-I. Kim, D. S. Hwang, H. E. Jeong, and H. Ko, "Ultra-adaptable and wearable photonic skin based on a shape-memory, responsive cellulose derivative," *Responsive Cellulose Derivative*, vol. 29, no. 34, 2019, Art. no. 1902720.

[2] W. Hou, Z. Ning, L. Guo, and X. Zhang, "Temporal, functional and spatial big data computing framework for large-scale smart grid," *IEEE Trans. Emerg. Topics Comput.*, vol. 7, no. 3, pp. 369–379, Jul. 2019.

[3] W. Hou, L. Guo, and Z. Ning, "Local electricity storage for blockchain-based energy trading in industrial Internet of Things," *IEEE Trans. Ind. Informat.*, vol. 15, no. 6, pp. 3610–3619, Jun. 2019.

[4] B. V. Vishakh and M. K. Khwaja, "Wearable device for hearing impaired individuals using ZigBee protocol," in *Proc. 9th Asia Modelling Symp. (AMS)*, Sep. 2015, pp. 181–184.

[5] A. I. Hussein, "Wearable computing: Challenges of implementation and its future," in *Proc. 2015 12th Learn. Technol. Conf.*, Apr. 2015, pp. 14–19.

[6] Y. Jin, "Low-cost and active control of radiation of wearable medical health device for wireless body area network," *J. Med. Syst.*, vol. 43, no. 5, p. 137, 2019.

[7] R. T. Li, S. R. Kling, M. J. Salata, S. A. Cupp, J. Sheehan, and J. E. Voos, "Wearable performance devices in sports medicine," *Sports Health*, vol. 8, no. 1, pp. 74–78, Jan. 2016.

[8] K. Kaewkannate and S. Kim, "A comparison of wearable fitness devices," *BMC Public Health*, vol. 16, no. 1, p. 433, 2016.

[9] Z. Ning, F. Xia, N. Ullah, X. Kong, and X. Hu, "Vehicular social networks: Enabling smart mobility," *IEEE Commun. Mag.*, vol. 55, no. 5, pp. 16–55, May 2017.

[10] Z. Ning, P. Dong, and X. Wang, "Mobile edge computing enabled 5G health monitoring for Internet of medical things: A decentralized game theoretic approach," *IEEE J. Sel. Areas Commun.*, to be published.

[11] W. Saadeh, S. A. Butt, and M. A. B. Altaf, "A patient-specific single sensor IoT-based wearable fall prediction and detection system," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 27, no. 5, pp. 995–1003, May 2019.

[12] G. Fang and E. Dutkiewicz, "BodyMAC: Energy efficient TDMA-based MAC protocol for wireless body area networks," in *Proc. ISCIT*, 2009, pp. 1455–1459.

[13] S. Marinkovic, C. Spagnol, and E. Popovici, "Energy-efficient TDMA-based MAC protocol for wireless body area networks," in *Proc. SENSORCOMM*, Athens, Greece, 2009, pp. 604–609.

[14] S. A. Rokni and H. Ghasemzadeh, "Autonomous sensor-context learning in dynamic human-centered Internet-of-Things environments," in *Proc. 35th Int. Conf. Comput.-Aided Design (ICCAD)*, 2016, pp. 1–6.

[15] Z. Ning, X. Hu, Z. Chen, M. Zhou, B. Hu, J. Cheng, and M. S. Obaidat, "A cooperative quality-aware service access system for social Internet of Vehicles," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2506–2517, Aug. 2018.

[16] M. Jia, Z. Yin, D. Li, Q. Guo, and X. Gu, "Toward improved offloading efficiency of data transmission in the IoT-cloud by leveraging secure truncating OFDM," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 4252–4261, Jun. 2019.

[17] M. Jia, Z. Yin, Q. Guo, G. Liu, and X. Gu, "Downlink design for spectrum efficient IoT network," *IEEE Internet Things J.*, vol. 5, no. 5, pp. 3397–3404, Oct. 2018.

[18] T.-Y. Kim, S. Youm, J.-J. Jung, and E.-J. Kim, "Multi-hop WBAN construction for healthcare IoT systems," in *Proc. Int. Conf. Platform Technol. Service*, Jan. 2015, pp. 27–28.

[19] G. Cai, Y. Fang, J. Wen, G. Han, and X. Yang, "QoS-aware buffer-aided relaying implant WBAN for healthcare IoT: Opportunities and challenges," *IEEE Netw.*, vol. 33, no. 4, pp. 96–103, Jul. 2019.
[20] Z. Ning, F. Xia, X. Hu, Z. Chen, and M. S. Obaidat, "Social-oriented adaptive transmission in opportunistic Internet of smartphones," *IEEE Trans. Ind. Informat.*, vol. 13, no. 2, pp. 810–820, Apr. 2017.
[21] Z. Ning, X. Wang, X. Kong, and W. Hou, "A social-aware group formation framework for information diffusion in narrowband Internet of Things," *IEEE Internet Things J.*, vol. 5, no. 3, pp. 1527–1538, Jun. 2018.
[22] K. Fehl, D. J. Van Der Post, and D. Semmann, "Co-evolution of behaviour and social network structure promotes human cooperation," *Ecol. Lett.*, vol. 14, no. 6, pp. 546–551, Jun. 2011.
[23] V. Y. Kishorbhai and N. N. Vasantbhai, "AON: A survey on emergency communication systems during a catastrophic disaster," *Procedia Comput. Sci.*, vol. 115, pp. 838–845, 2017.
[24] Z. Ning, X. Wang, J. J. P. C. Rodrigues, and F. Xia, "Joint computation offloading, power allocation, and channel assignment for 5G-enabled traffic management systems," *IEEE Trans. Ind. Informat.*, vol. 15, no. 5, pp. 3058–3067, May 2019.
[25] M. Boumaiz, M. E. Ghazi, S. Mazer, M. Fattah, A. Bouayad, M. E. Bekkali, and Y. Balboul, "Energy harvesting based WBANs: EH optimization methods," *Procedia Comput. Sci.*, vol. 151, pp. 1040–1045, 2019.
[26] M. Cicioğlu and A. Çalhan, "SDN-based wireless body area network routing algorithm for healthcare architecture," *ETRI J.*, vol. 41, no. 4, pp. 452–464, Aug. 2019.
[27] A. S. Abiodun, M. H. Anisi, and M. K. Khan, "Cloud-based wireless body area networks: Managing data for better health care," *IEEE Consum. Electron. Mag.*, vol. 8, no. 3, pp. 55–59, May 2019.
[28] R. M. D. Omer and N. K. A. Salihi, "HealthMate: Smart wearable system for health monitoring (SWSHM)," in *Proc. ICNSC*, Calabria, Italy, 2017, pp. 755–760.
[29] M. Sandhu, M. Akbar, M. Behzad, N. Javaid, Z. Khan, and U. Qasim, "Mobility model for WBANs," in *Proc. BWCCA*, Kraków, Poland, 2015, pp. 155–160.
[30] Y. Liu, D. Liu, and G. Yue, "BGMM: A body gauss-Markov based mobility model for body area networks," *Tinshhua Sci. Technol.*, vol. 23, no. 3, pp. 277–287, Jun. 2018.
[31] Y. Yin, F. Hu, L. Cen, Y. Du, and L. Wang, "Balancing long lifetime and satisfying fairness in WBAN using a constrained Markov decision process," *Int. J. Antennas Propag.*, vol. 2015, Mar. 2015, Art. no. 657854.
[32] P. T. Hiep and N. Huy Hoang, "Payload and power consumption analysis of IEEE802.15.6 based WBAN with CSMA/CA," in *Proc. ATC*, Ho Chi Minh City, Vietnam, 2015, pp. 500–505.
[33] Y. Yang, D. Shen, and E. Dutkiewicz, "Channel model for in-body WBAN," in *Proc. APSURSI*, Newport Beach, CA, USA, 2012, pp. 1–2.
[34] A. Awang and U. F. Abbasi, "Performance evaluation of cross-layer opportunistic mac/routing with node's mobility for wireless body area networks," in *Proc. MICC*, Kuching, Malaysia, 2015, pp. 30–35.
[35] S. Misra, N. Islam, J. Mahapatro, and M. Mahadevappa, "Random room mobility model and extra-wireless body area network communication in hospital buildings," *IET Netw.*, vol. 4, no. 1, pp. 54–64, Jan. 2015.
[36] Y. Liao, Y. Han, Q. Yu, Q. Ai, Q. Liu, and M. S. Leeson, "Wireless body area network mobility-aware task offloading scheme," *IEEE Access*, vol. 6, pp. 61366–61376, 2018.
[37] Y. D. Wang and Y. Liu, "Analysis and comparison of WSN routing protocols oriented to WBAN," *Appl. Mech. Mater.*, vols. 241–244, pp. 952–955, Dec. 2012.
[38] R. Kumari and P. Nand, "Performance comparison of various routing protocols in WSN and WBAN," in *Proc. ICNC*, Silicon Valley, CA, USA, 2017, pp. 427–431.
[39] J.-Y. Chang and P.-H. Ju, "An energy-saving routing architecture with a uniform clustering algorithm for wireless body sensor networks," *Future Gener. Comput. Syst.*, vol. 35, pp. 128–140, Jun. 2014.
[40] N. Sangeetha Priya, R. Sasikala, S. Alavandar, and L. Bharathi, "Security aware trusted cluster based routing protocol for wireless body sensor networks," *Wireless Personal Commun*, vol. 102, no. 4, pp. 3393–3411, Oct. 2018.
[41] M. Roy, C. Chowdhury, and N. Aslam, "Designing 2-hop interference aware energy efficient routing (HIER) protocol for wireless body area networks," in *Proc. COMSNETS*, Bengaluru, India, 2017, pp. 262–283.
[42] N. Ababneh, N. Timmons, and J. Morrison, "EBRAR: Energy-balanced rate allocation and routing protocol for body area networks," in *Proc. ISCC*, Cappadocia, Turkey, 2012, pp. 000475–000478.
[43] L. Hu, Y. Zhang, and D. Feng, "Design of QoS-aware multi-level MAC-layer for wireless body area network," *J. Med. Syst.*, vol. 39, no. 12, p. 192, 2015.
[44] Z. A. Khan, M. B. Rasheed, and N. Javaid, "Effect of packet inter-arrival time on the energy consumption of beacon enabled MAC protocol for body area networks," *Procedia Comput. Sci.*, vol. 32, pp. 579–586, 2014.
[45] X. Yuan, C. Li, L. Yang, S. Ullah, and Y. Song, "On energy-saving in e-healthcare: A directional MAC protocol for WBAN," in *Proc. GLOBECOM*, San Diego, CA, USA, 2015, pp. 1–6.
[46] S. Cotton and W. Scanlon, "Using smart people to form future mobile wireless networks," *Microw. J.*, vol. 54, no. 12, pp. 24–40, 2011.
[47] M. M. Alam and E. B. Hamida, "Interference mitigation and coexistence strategies in IEEE 802.15.6 based wearable body-to-body networks," in *Proc. CROWNCOM*, Doha, Qatar, 2015, pp. 665–677.
[48] S. M. Shimly, D. B. Smith, and S. Movassaghi, "Cross-layer designs for body-to-body networks: Adaptive CSMA/CA with distributed routing," in *Proc. ICC*, Kansas City, MO, USA, 2018, pp. 1–6.
[49] T. A. Ramrekha and C. Politis, "A hybrid adaptive routing protocol for extreme emergency ad hoc communication," in *Proc. ICCCN*, Zürich, Switzerland, 2010, pp. 1–6.
[50] S. Maity, D. Das, S. Sen, and X. Jiang, "Secure human-Internet using dynamic human body communication," in *Proc. ISLPED*, Taipei, Taiwan, 2017, pp. 1–6.
[51] F. Wu, T. Y. Wu, and M. R. Yuce, "Design and implementation of a wearable sensor network system for IoT-connected safety and health applications," in *Proc. WF-IoT*, Limerick, Ireland, 2019, pp. 87–90.
[52] J. Kraaier and U. Killat, "The random waypoint city model-user distribution in a street-based mobility model for wireless network simulations," in *Proc. ACM 3rd ACM Int. Workshop Wireless Mobile Appl. Services WLAN Hotspots*, New York, NY, USA, 2015, pp. 100–103.
[53] Y. Cai, X. Wang, Z. Li, and Y. Fang, "Delay and capacity in MANETs under random walk mobility model," *Wireless Netw.*, vol. 20, no. 3, pp. 525–536, Apr. 2014.
[54] S. Chen, J. Zhang, and G. Wang, "Analysis of random direction mobility model with uniformly accelerated motion for ad hoc networks," *J. Comput. Inf. Syst.*, vol. 10, no. 5, pp. 5339–5346, 2014.
[55] Z. Ning, K. Zhang, and X. Wang, "Joint computing and caching in 5G-envisioned Internet of vehicles: A deep reinforcement learning based traffic control system," *IEEE Trans. Intell. Transp. Syst.*, to be published.
[56] T. Camp, J. Boleng, and V. Davies, "A survey of mobility models for ad hoc network research," *Wireless Commun. Mobile Comput.*, vol. 2, no. 5, pp. 483–502, Aug. 2002.
[57] M. Ali, H. Moungla, and M. Younis, "Inter-WBANs interference mitigation using orthogonal Walsh hadamard codes," in *Proc. IEEE 27th Annu. Int. Symp. Personal, Indoor, Mobile Radio Commun. (PIMRC)*, Sep. 2016, pp. 1–7.
[58] S. Huang, B. Guo, W. Ju, X. Zhang, J. Han, C. Phillips, J. Zhang, and W. Gu, "A novel framework and the application mechanism with cooperation of control and management in multi-domain WSON," *J. Netw. Syst. Manage.*, vol. 21, no. 3, pp. 453–473, Sep. 2013, doi: 10.1007/s10922-012-9242-4.
[59] A. Manirabona, S. Boudjit, and L. C. Fourati, "Energy aware routing protocol for inter WBANs cooperative communication," in *Proc. ISNCC*, Tunis, Tunisia, 2015, pp. 1–6.
[60] J. Dong and D. Smith, "Coexistence and interference mitigation for wireless body area networks: Improvements using on-body opportunistic relaying," *Duke Math. J.*, to be published.
[61] Z. Bie, H. Xu, and W. Xiao, "Energy-aware geo-routing for delay tolerant networks in disaster areas," in *Proc. ICCNT*, Dalian, China, 2013, pp. 694–698.
[62] L. Guo, Z. Ning, W. Hou, B. Hu, and P. Guo, "Quick answer for big data in sharing economy: Innovative computer architecture design facilitating optimal service-demand matching," *IEEE Trans. Autom. Sci. Eng.*, vol. 15, no. 4, pp. 1494–1506, Oct. 2018.
[63] A. Meharouech, J. Elias, and A. Mehaoua, "A two-stage game theoretical approach for interference mitigation in body-to-body networks," *Comput. Netw.*, vol. 95, pp. 15–34, Feb. 2016.
[64] R. Kazemi, R. Vesilo, and E. Dutkiewicz, "Inter-network interference mitigation in Wireless Body Area Networks using power control games," in *Proc. ISCIT*, Tokyo, Japan, 2010, pp. 81–86.
[65] J. Wang, Y. Sun, and Y. Ji, "Priority-based capacity and power allocation in co-located WBANs using Stackelberg and bargaining games," *J. Supercomput.*, vol. 74, no. 7, pp. 3114–3147, 2018.

[66] X. Lv, X. Li, Y. Li, and L. Liu, "Research of opportunistic routing protocol in wearable sensor network," in *Proc. IEEE Asia–Pacific Conf. Wearable Comput. Syst.*, 2010, pp. 99–103.
[67] J. Jiang, Y. Liu, F. Song, R. Du, and M. Huang, "The routing algorithm based on fuzzy logic applied to the individual physiological monitoring wearable wireless sensor network," *J. Elect. Comput. Eng.*, vol. 2015, Nov. 2015, Art. no. 546425.
[68] C. Abreu, M. Ricardo, and P. M. Mendes, "Energy-aware routing for biomedical wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 40, no. 1, pp. 270–278, 2014.
[69] A. Meharouech, J. Elias, and A. Mehaoua, "Joint epidemic control and routing in mass gathering areas using body-to-body networks," in *Proc. IWCMC*, Valencia, Spain, 2017, pp. 1759–1764.
[70] W. Fan, Z. Xie, and W. Yu, "Research on CPN-based inter-WBANs scheduling algorithm," *Mobile Commun.*, vol. 39, no. 8, pp. 66–74, 2015.
[71] C. Yi and J. Cai, "A truthful mechanism for prioritized medical packet transmissions in beyond-WBANs," in *Proc. GLOBECOM*, Singapore, 2017, pp. 1–6.
[72] C. Y. Huang, M. L. Liu, and S. H. Cheng, "WRAP: A weighted random value protocol for multiuser wireless body area network," in *Proc. ISSTA*, Trento, Italy, 2010, pp. 116–119.
[73] M. M. Alam, D. B. Arbia, and E. B. Hamida, "Wearable wireless sensor networks for emergency response in public safety networks," *Wireless Public Saf. Netw.*, vol. 2, pp. 63–94, Jan. 2016.
[74] M. S. Abdalzaher and H. A. Elsayed, "Employing data communication networks for managing safer evacuation during earthquake disaster," *Simul. Model. Pract. Theory*, vol. 94, pp. 379–394, Jul. 2019.
[75] D. Macone, G. Oddi, and A. Pietrabissa, "MQ-routing: Mobility-, GPS- and energy-aware routing protocol in MANETs for disaster relief scenarios," in *Ad Hoc Networks*. Amsterdam, The Netherlands: Elsevier, 2013.
[76] S. Zhang, H. Guo, and K. Zhu, "Multistage assignment optimization for emergency rescue teams in the disaster chain," *Knowl.-Based Syst.*, vol. 137, pp. 123–137, Dec. 2017.
[77] S. M. George, Z. W. Hou, M. Won, Y. O. Lee, A. Pazarloglou, R. Stoleru, P. Barooah, and H. Chenji, "DistressNet: A wireless ad hoc and sensor network architecture for situation management in disaster response," *IEEE Commun. Mag.*, vol. 48, no. 3, pp. 128–136, Mar. 2010.
[78] E. Onem, S. Eryigit, A. Akurgal, and T. Tugcu, "QoS-enabled spectrum-aware routing for disaster relief and tactical operations over cognitive radio ad hoc networks," in *Proc. MILCOM*, Baltimore, MD, USA, 2014, pp. 1109–1115.
[79] Y. Jahir, M. Atiquzzaman, H. Refai, A. Paranjothi, and P. G. Lopresti, "Routing protocols and architecture for disaster area network: A survey," *Ad Hoc Netw.*, vol. 82, pp. 1–14, Jan. 2019.
[80] M. M. Alam, M. Rehmani, A. Pathan, and E. B. Hamida, "Wearable wireless sensor networks: Applications, standards, and research trends," *Emerging Communication Technologies Based on Wireless Sensor Networks: Current Research and Future Applications*. Boca Raton, FL, USA: CRC Press, 2015.
[81] E. B. Hamida, M. M. Alam, and M. Maman, "Wearable body-to-body networks for critical and rescue operations—The CROW^2 project," in *Proc. PIMRC*, Washington DC, USA, 2014, pp. 2145–2149.
[82] M. M. Alam, D. B. Arbia, and E. B. Hamida, "Research trends in multi-standard device-to-device communication in wearable wireless networks," in *Cognitive Radio Oriented Wireless Networks*. Cham, Switzerland: Springer, 2015.
[83] Y. Lin, X. Wang, L. Zhang, P. Li, D. Zhang, and S. Liu, "The impact of node velocity diversity on mobile opportunistic network performance," *J. Netw. Comput. Appl.*, vol. 55, pp. 47–58, Sep. 2015.
[84] D. B. Arbia, M. M. Alam, E. Ben Hamida, and R. Attia, "Data dissemination strategies for emerging wireless body-to-body networks based Internet of humans," in *Proc. IEEE 11th Int. Conf. Wireless Mobile Comput., Netw. Commun. (WiMob)*, Oct. 2017, pp. 1–8.
[85] N. Aschenbruck, E. Gerhards-Padilla, and P. Martini, "Modeling mobility in disaster area scenarios," *Perform. Eval.*, vol. 66, no. 12, pp. 773–790, Dec. 2009.
[86] N. Aschenbruck, M. Frank, J. Tolle, and P. Martini, "Human mobility in manet disaster area simulation—A realistic approach," in *Proc. 29th Annu. IEEE Int. Conf. Local Comput. Netw.*, Nov. 2004, pp. 668–675.
[87] M. Y. S. Uddin, H. Ahmadi, R. Kravets, and T. Abdelzaher, "A low-energy, multi-copy inter-contact routing protocol for disaster response networks," in *Proc. 6th Annu. IEEE Commun. Soc. Conf. Sensor, Mesh Ad Hoc Commun. Netw.*, Jun. 2009, pp. 1–9.
[88] S. Huang, B. Guo, X. Li, J. Zhang, Y. Zhao, and W. Gu, "Pre-configured polyhedron based protection against multi-link failures in optical mesh networks," *Opt. Express*, vol. 22, no. 3, pp. 2386–2402, Feb. 2014, doi: 10.1364/oe.22.002386.
[89] A. Samanta and S. Misra, "Energy-efficient and distributed network management cost minimization in opportunistic wireless body area networks," *IEEE Trans. Mobile Comput.*, vol. 17, no. 2, pp. 376–389, Feb. 2018.
[90] D. Ben Arbia, M. M. Alam, R. Attia, and E. Ben Hamida, "ORACE-net: A novel multi-hop body-to-body routing protocol for public safety networks," *Peer-Peer Netw. Appl.*, vol. 10, no. 3, pp. 726–749, May 2017.
[91] M. Ambigavathi and D. Sridharan, "Priority based AODV routing protocol for critical data in wireless body area network," in *Proc. ICSP*, 2015, pp. 1–5.
[92] S. Adhikary, S. Choudhury, and S. Chattopadhyay, "A new routing protocol for WBAN to enhance energy consumption and network lifetime," in *Proc. ICDCN*, Singapore, 2016, pp. 1–6.
[93] S. Ullah, A. Vasilakos, H.-C. Chao, and J. Suzuki, "Cloud-assisted wireless body area networks," *Inf. Sci.*, vol. 284, pp. 81–83, Nov. 2014.
[94] M. Feng, W. Xiao, and Y. Zhang, "Multi-objective particle swarm optimization for resource allocation in cloud computing," in *Proc. CCIS*, Shanghai, China, 2013, pp. 1161–1165.
[95] A. Samanta and Y. Li, "Distributed pricing policy for cloud-assisted body-to-body networks with optimal QoS and energy considerations," *IEEE Trans. Services Comput.*, to be published.
[96] G. Almashaqbeh, T. Hayajneh, B. J. Mohd, and A. V. Vasilakos, "QoS-aware health monitoring system using cloud-based WBANs," *J. Med. Syst.*, vol. 38, no. 10, p. 121, 2014.
[97] S. Misra and S. Chatterjee, "Social choice considerations in cloud-assisted WBAN architecture for post-disaster healthcare: Data aggregation and channelization," *Inf. Sci.*, vol. 284, pp. 95–117, Nov. 2014.
[98] R. K. Barik, H. Dubey, and K. Mankodiya, "SOA-FOG: Secure service-oriented edge computing architecture for smart health big data analytics," in *Proc. GlobalSIP*, Anaheim, California, USA, 2018, pp. 477–481.
[99] Z. Ning, J. Huang, and X. Wang, "Vehicular fog computing: Enabling real-time traffic management for smart cities," *IEEE Wireless Commun.*, vol. 26, no. 1, pp. 87–93, Feb. 2019.
[100] X. Wang, Z. Ning, and L. Wang, "Offloading in Internet of vehicles: A fog-enabled real-time traffic management system," *IEEE Trans. Ind. Informat.*, vol. 14, no. 10, pp. 4568–4578, Oct. 2018.
[101] Z. Ning, X. Kong, F. Xia, W. Hou, and X. Wang, "Green and sustainable cloud of things: Enabling collaborative edge computing," *IEEE Commun. Mag.*, vol. 57, no. 1, pp. 72–78, Jan. 2019.
[102] W. Hou, Z. Ning, and L. Guo, "Green survivable collaborative edge computing in smart cities," *IEEE Trans. Ind. Informat.*, vol. 14, no. 4, pp. 1594–1605, Apr. 2018.
[103] Z. Ning, Y. Feng, M. Collotta, X. Kong, X. Wang, L. Guo, X. Hu, and B. Hu, "Deep learning in edge of vehicles: Exploring trirelationship for data transmission," *IEEE Trans. Ind. Informat.*, vol. 15, no. 10, pp. 5737–5746, Oct. 2019.
[104] Z. Ning, P. Dong, J. J. P. C. Rodrigues, F. Xia, and X. Wang, "Deep reinforcement learning for vehicular edge computing: An intelligent offloading system," *ACM Trans. Intell. Syst. Technol.*, vol. 10, no. 6, pp. 1–24, 2019.
[105] Z. Ning, J. Huang, X. Wang, J. J. P. C. Rodrigues, and L. Guo, "Mobile edge computing-enabled Internet of vehicles: Toward energy-efficient scheduling," *IEEE Netw.*, vol. 33, no. 5, pp. 198–205, Sep. 2019.
[106] L. Guo, Z. Ning, Q. Song, F. Huang, and A. Jamalipour, "Joint encoding and grouping multiple node pairs for physical-layer network coding with low-complexity algorithm," *IEEE Trans. Veh. Technol.*, vol. 66, no. 10, pp. 9275–9286, Oct. 2017.
[107] S. Huang, W. Lian, X. Zhang, B. Guo, P. Luo, J. Zhang, and W. Gu, "A novel method to evaluate clustering algorithms for hierarchical optical networks," *Photonic Netw. Commun.*, vol. 23, no. 2, pp. 183–190, Apr. 2012, doi: 10.1007/s11107-011-0349-4.
[108] S. N. Ramli, R. Ahmad, and M. F. Abdollah, "A biometric-based security for data authentication in wireless body area network (WBAN)," in *Proc. ICACT*, Rajampet, India, 2013, pp. 998–1001.
[109] M. Jia, D. Li, Z. Yin, Q. Guo, and X. Gu, "High spectral efficiency secure communications with nonorthogonal physical and multiple access layers," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 5954–5961, Aug. 2019.
[110] A. Tewari and P. Verma, "Security and privacy in e-healthcare monitoring with WBAN: A critical review," *Int. J. Comput. Appl.*, vol. 136, no. 11, pp. 37–42, Feb. 2016.

[111] W. Drira, E. Renault, and D. Zeghlache, "A hybrid authentication and key establishment scheme for WBAN," in *Proc. Trust, Secur. Privacy Comput. Commun. (TrustCom)*, Livepool, U.K., 2012, pp. 78–83.
[112] Z. Ning, Y. Li, P. Dong, X. Wang, M. S. Obaidat, X. Hu, L. Guo, Y. Guo, J. Huang, and B. Hu, "When deep reinforcement learning meets 5G-enabled vehicular networks: A distributed offloading framework for traffic big data," *IEEE Trans. Ind. Informat.*, vol. 16, no. 2, pp. 1352–1361, Feb. 2020, doi: 10.1109/tii.2019.2937079.
[113] X. Wang, Z. Ning, X. Hu, L. Wang, L. Guo, B. Hu, and X. Wu, "Future communications and energy management in the Internet of vehicles: Toward intelligent energy-harvesting," *IEEE Wireless Commun.*, vol. 26, no. 6, pp. 87–93, Dec. 2019, doi: 10.1109/mwc.001.1900009.
[114] Z. Ning, L. Liu, F. Xia, B. Jedari, I. Lee, and W. Zhang, "CAIS: A copy adjustable incentive scheme in community-based socially aware networking," *IEEE Trans. Veh. Technol.*, vol. 66, no. 4, pp. 3406–3419, Apr. 2017.
[115] M. Jia, X. Gu, Q. Guo, W. Xiang, and N. Zhang, "Broadband hybrid satellite-terrestrial communication systems based on cognitive radio toward 5G," *IEEE Wireless Commun.*, vol. 23, no. 6, pp. 96–106, Dec. 2016.
[116] M. Jia, Z. Gao, Q. Guo, Y. Lin, and X. Gu, "Sparse feature learning for correlation filter tracking toward 5G-enabled tactile Internet," *IEEE Trans. Ind. Informat.*, vol. 16, no. 3, pp. 1904–1913, Mar. 2020.
[117] Z. Ning, X. Wang, and J. Huang, "Mobile edge computing-enabled 5G vehicular networks: Toward the integration of communication and computing," *IEEE Veh. Technol. Mag.*, vol. 14, no. 1, pp. 54–61, Mar. 2019.
[118] M. Jia, X. Wang, and Q. Guo, "Performance analysis of cooperative non-orthogonal multiple access based on spectrum sensing," *IEEE Trans. Veh. Technology.*, vol. 6, no. 7, pp. 6855–6866, 2019.
[119] M. Jia, X. Zhang, Q. Guo, Y. Li, P. Lin, and X. Gu, "Interbeam interference constrained resource allocation for shared spectrum multibeam satellite communication systems," *IEEE Internet Things J.*, vol. 6, no. 4, pp. 6052–6059, Sep. 2019.
[120] M. Jia, L. Wang, and Q. Guo, "A low complexity detection algorithm for fixed up-link SCMA system in mission critical scenario," *IEEE Internet Things J.*, vol. 5, no. 5, pp. 3289–3297, Apr. 2018.
[121] S. Huang, B. Li, and B. Guo, "Distributed protocol for removal of loop backs with asymmetric digraph using GMPLS in p-cycle based optical networks," *IEEE Trans. Commun.*, vol. 59, no. 2, pp. 541–551, Dec. 2011.
[122] S. Huang, Y. Zhou, J. Zhang, P. Luo, D. Tan, W. Gu, and S. Yin, "Fragmentation assessment based on-line routing and spectrum allocation for intra-data-center networks with centralized control," *Opt. Switching Netw.*, vol. 14, pp. 274–281, 2014.
[123] S. Huang, J. Li, J. Zhou, and W. Gu, "Novel spectrum properties of the periodic π-phase-shifted fiber Bragg grating," *Opt. Commun.*, vol. 285, no. 6, pp. 1113–1117, Mar. 2012.
[124] S. Huang, J. Li, Y. Ye, P. Shi, J. Zhou, B. Guo, and W. Gu, "The further investigation of the true time delay unit based on discrete fiber Bragg gratings," *Opt. Laser Technol.*, vol. 44, no. 4, pp. 776–780, Jun. 2012.

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