Intelligent Transportation Spaces: Vehicles, Traffic, Communications, and Beyond

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ABSTRACT

Recent years have witnessed numerous technical breakthroughs in electronics, computing, sensing, robotics, control, signal processing, and communications. These have significantly advanced the state of applications of intelligent transportation systems. More recently, as one leading effort toward the cyber-physical-social system, the concept of intelligent transportation spaces was proposed to further improve the vehicles, traffic, and transportation safety, efficiency and sustainability. ITSp integrate not only various ITS modules, but also pedestrians, vehicles, roadside infrastructures, traffic management centers, sensors, and satellites. With distributed and pervasive intelligence, ITSp clearly impose some stringent requirements on the information exchange among all entities within the ITSp, in terms of the information availability, reliability, fidelity, and timeliness. These requirements, together with the high mobility of vehicles and the highly variable network topology, make the communications and networking for ITSp very challenging. This article will introduce the concept of ITSp and analyze possible communication technology candidates for ITSp. Further discussions will also be provided at the end of this article.

INTRODUCTION

In the past 125 years since the first automobile was invented around 1885,[1] people have never stopped seeking ways to improve vehicles, traffic, and transportation systems for safety, comfort, efficiency, and environmental sustainability. However, our existing transportation systems are far from satisfactory in all these counts. In recent years, the U.S. has experienced about 42,000 road traffic fatalities and about 2 million injury-causing crashes [1]. The car accident and fatality rates are even higher in developing countries. In China, 99,217 persons died in traffic accidents in 2004 alone and one third of these were pedestrians [2]. Additionally, the increasing number of vehicles has led to traffic congestions and low vehicle speeds. For example, in Japan, the mean vehicle speed in urban areas was only 20 km/h in 1995 and 25km/h in 2005 [3]. These not only significantly limit the transportation and fuel efficiency, but also increase the exhaust emission. On the other hand, with our current technologies, the vehicles can only use less than 5 percent of the highway surface in order to keep a safe vehicle-to-vehicle distance, according to the data provided by the California's Performance Measurement System (PeMS) [4]. This alarmingly small usage is clearly a waste of the transportation resource. All these merge into an urgent call for safer, more efficient, and more sustainable transportation solutions.

To answer this urgent call, intelligent transportation systems (ITS) exploit technologies from multiple disciplines to improve the current transportation systems in all aspects by increasing traffic information, reducing driving loads, and enhancing route management. In recent years, technical breakthroughs in electronics, computing, sensing, robotics, control, signal processing, and communications have advanced the state of applications of ITS [5]. There are many existing ITS modules as well as emerging ones under research, development, and deployment. Examples include automatic toll collection, safety information broadcasting, routing management according to the realtime traffic conditions, collision avoidance, adaptive cruise control, emergency vehicle operation, winter road maintenance, public transport management, driver health condition monitoring, and autonomous driving, just to name a few. Each category of the ITS modules may have different mechanisms. For example, the collision avoidance ITS module can collect information of adjacent vehicles by using optical/microwave sensors or by listening to other vehicles' broadcast, and then react by sending warning messages to the driver, automatically slowing down the vehicle, or completely taking over the driving before the collision threaten is dismissed. Multiple ITS modules are adopted in vehicles, roadside infrastructures, and traffic management centers to improve different

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[1] *Since there are many different types of automobiles, exactly who invented the automobile is a matter of opinion. Many suggest that Karl Benz created the first true automobile in 1885.*

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aspects in our transportation systems. Various ITS provide promising solutions towards safer and more efficient transportation. However, their abundance may also incur problems as illustrated in the following example. Imagine a scenario in which a vehicle and roadside infrastructures are equipped with multiple ITS modules. At a certain time, multiple events may occur simultaneously: the information broadcasting system broadcasts the current traffic condition; the realtime adaptive routing system indicates that the preset route has been changed according to the current traffic condition; the collision avoidance system warns that the vehicle is too close to its neighbors; and the driver health monitoring system suggests the driver to take a break according to the driver's electroencephalogram (EEG). The driver could be overwhelmed by a vast amount of information and the required reactions. Research in [6] shows that offering the driver information increases the driver's workload which, when exceeding a certain level, can cause severe accidents. Today's ITS are mostly designed and operated independently for their individual specific purposes, and lack the capability of jointly accommodating the driver's best interest and reasonable workload. Additionally, independently designed ITS modules may conflict in other aspects, such as the communication frequency bands, display and voice indication to the driver, and power supply.

In 1999, the term *intelligent transportation spaces* (ITSp) was coined in [7] and this concept was further illustrated in [8]. ITSp integrate multiple ITS modules, as well as the participants and devices in transportation, such as pedestrians, vehicles, roadside infrastructures, traffic management centers, sensors, and satellites into spaces with distributed and pervasive intelligence (Fig. 1). With the interlaced cyber, physical and social aspects, ITSp can also benefit from the emerging cyber-physical and cyber-physical-social system (CPS/CPSS) research [9, 10]. ITSp not only solve potential conflicts in independent ITS modules by integrated design, but also maximize resource sharing among different applications. For example, the video information from the cameras placed at intersections for traffic monitoring may also be used for pedestrian activity cognition, and the realtime EEG information that reflects the reaction delay of the driver may also be employed to adjust the safe vehicle distances managed by the collision avoidance system.

However, realization of ITSp is undoubtedly challenging, especially in terms of the information exchange among all nodes within the space, in comparison with traditional ITS. First, information should be available anywhere within the space as needed and with tolerable delay, as if there is an omnipresent medium. Secondly, the nodes within the space, such as vehicles, sensors, and infrastructures, should be able to manage and exchange information intelligently on their own since the workload of drivers should be limited for the sake of safety.

Of course, the communications for ITSp have their own requirements and limiting factors. The information to be exchanged can be divided into non-safety-related messages and safety-related ones. The latter have very stringent latency and reliability requirements while the former can be bandwidth demanding. In addition, the inherent characteristics of vehicles, such as high mobility and limited intra-vehicle distance, give rise to new challenges for establishing communication links in ITSp. In the sequel, we will elaborate on possible communication technologies for ITSp, with a focus on the wireless ones (Fig. 2).

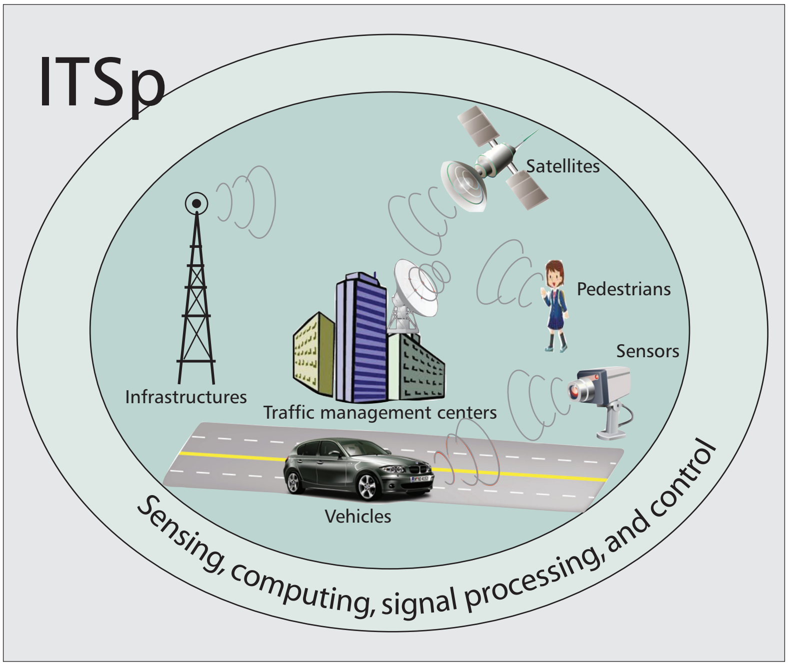

Figure 1. *ITSp integrates multiple ITS modules as well as multiple technologies.*

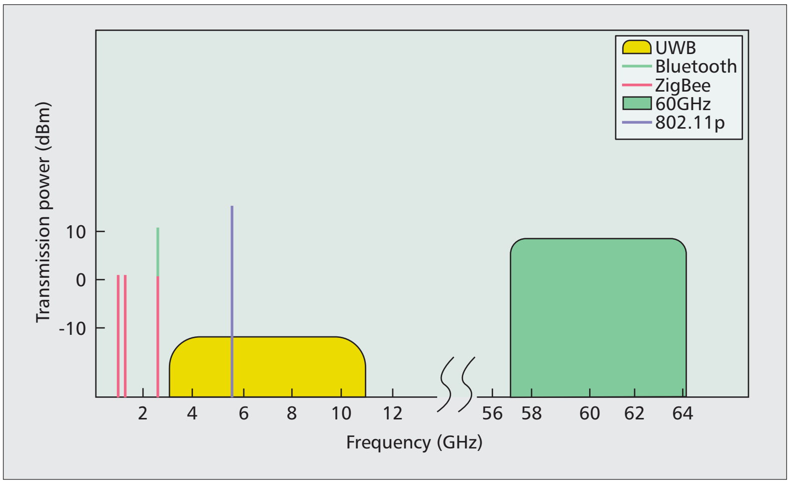

Figure 2. *Frequency bands and typical transmission power of possible communication technology candidates for ITSp.*

COMMUNICATIONS INSIDE VEHICLES

In the past decades, the development of vehicle electronics has led to a significant increase in the number of connecting cables within a vehicle. The connecting cables can contribute up to 50kg to the vehicle mass. Cables and their accessory components embedded and distributed throughout the vehicle body can be costly and difficult

Characteristic	Bluetooth	ZigBee
IEEE spec.	802.15.1	802.15.4
Operating frequency	2.4 GHz ISM	868 MHz, 902–928 MHz, 2.4 GHz ISM
Data rate	1 Mb/s	20–250 kb/s
Nominal TX power	0–10 dBm	–25–0 dBm
Nominal range	10–100 m	10–75 m
Max # of cell nodes	8	65,000

Table 1. *Characteristics of Bluetooth and ZigBee.*

to install and maintain. The wireless communications technology, which happens to be first patented and experimented around the same time the first automobile was invented, becomes a natural solution. Wireless links based on Bluetooth technology corresponding to IEEE 802.15.1 were proposed to replace the cables inside a vehicle about 10 years ago. Although wireless links are flexible and economical alternatives to their wired counterparts, fully wireless vehicle bus systems are still far from reality. This is because various links have very different requirements, and Bluetooth is clearly not a universal solution. Moreover, in an intra-vehicle environment for ITSp, there are expected to be more wireless links connecting various ITS modules, devices, and sensors for information, autonomous control, and safety purposes with very different data rate, latency, and reliability needs. Hence, coexistence of multiple wireless communication technologies is envisioned to meet these needs. Since data rate is the most significant figure of merit in communications, we will discuss wireless technologies for the intra-vehicle part of ITSp in two categories with low and high data rates, respectively.

LOW RATE INTRA-VEHICLE LINKS

Low rate intra-vehicle links are sufficient for a majority of traditional sensors inside vehicles, since most sensors require a throughput of no more than 12kb/s. Examples include the sensors for temperature, fuel level, and parking brake. Some new applications in ITSp also only require a low data rate of less than 1Mb/s, including the transmission of voice, vehicle control command, vehicle position information, and route information.

Bluetooth and ZigBee — Bluetooth as specified in IEEE 802.15.1 is a good candidate wireless technology for low rate intra-vehicle ITSp links due to its maturity. In fact, there have already been a number of Bluetooth-enabled intra-vehicle applications. Bluetooth global positioning system (GPS) receivers were widely used a few years ago when most of the personal digital assistants (PDAs) and smart phones did not come with an integrated GPS receiver. Nowadays, Bluetooth hands-free cell phone kits and Bluetooth music players are increasingly popular.

Of course, applications of Bluetooth in ITSp are not without problems. The transmission power of a Bluetooth node is typically 0–10 dBm, which is too high for a battery-driven device to continuously operate. Hence, the main power conserving mechanism of Bluetooth nodes is sleeping. The wakeup time of a sleeping node is about 3 seconds. In order to meet the stringent latency restrictions of low data rate ITSp links that convey control commands and safety-related information, intra-vehicle Bluetooth nodes are clearly not allowed to sleep much. Although some Bluetooth nodes can be powered by the automobile battery, many have to rely on the device embedded battery since an additional power cord could completely offset the benefits of wireless. The high power consumption along with limited sleep time can deplete the battery in hours. Another concern is the multiple access capability. The limitation of 8 nodes (1 master and 7 slaves) could be a bottleneck in ITSp where many sensors and devices may be connected to a single on-board computer.

Another promising candidate for low rate intra-vehicle ITSp wireless links is ZigBee as specified in IEEE 802.15.4. A comparison of technical specifications between Bluetooth and ZigBee is shown in Table 1. Besides the 2.4 GHz industrial, scientific, and medical (ISM) band as Bluetooth, ZigBee can operate on two additional bands, namely 868MHz and 902–928 MHz, providing more flexibility. Unlike Bluetooth, ZigBee allows for more than 65,000 nodes in a single network. The transmission power of ZigBee is –25–0 dBm, which is considerably lower than that of Bluetooth. Moreover, the ZigBee nodes can be waken up within 15 ms. This nice feature allows the transmission device to remain sleeping most of the time, which preserves the device's battery power. As stated in [11], ZigBee is designed to "run for six months to two years on just two AA batteries."

Coexistence Issues — Thanks to the features mentioned above, ZigBee is expected to play an important role in ITSp and has recently attracted increasing interests for low data rate intra-vehicle wireless communications. As a mature technology with many existing applications and featured with higher data rate, Bluetooth is also feasible for some intra-vehicle applications. Since these two technologies share the same 2.4 GHz ISM band and have comparable transmit power, in a vehicle with limited size, interference among devices adopting these two technologies is inevitable. However, research on the coexistence of Bluetooth and ZigBee is still very limited. Results in [12] show that the goodput performance of ZigBee in an intra-vehicle environment can be significantly affected by the Bluetooth interference. In the experiment, goodput decreases of 3–40 percent were observed for the ZigBee based nodes. The coexistence issue of Bluetooth and ZigBee will clearly be at the center of intra-vehicle communications research.

Intra-Vehicle Wireless Channel for Low Rate Communications — Presently, research on low rate intra-vehicle communication schemes other than Bluetooth and ZigBee is rarely reported. The development of ITSp arises the need for new low rate intra-vehicle communication technologies. In designing wireless communication technologies, channel characteristics are critical. As pointed out in [13], the "intra-vehicle environment is quite different from a typical indoor environment as the vehicle normally has a confined yet reflective environment with reflections that might be absorbed due to the presence of seats and plastic." Hence, the existing indoor channel models cannot be directly borrowed and extensive research on intra-vehicle wireless channel is needed.

HIGH RATE INTRA-VEHICLE LINKS

With the development of various ITS modules, more and more intra-vehicle applications require wireless links with high data rates on the order of hundreds of Mb/s. Examples include raw sampled data from vision/microwave sensors and multimedia data involving high quality music and video. With the emerging concept of the ITSp, high data rate intra-vehicle links are also recognized as an essential enabler for the computational data exchange of distributed artificial intelligence. Next, we will discuss some promising wireless technologies in this regime.

Ultra-Wideband Technology — The huge ultra-wideband (UWB) spectrum of 3.1–10.6 GHz supports high data rate communications up to 480Mb/s at a short distance of 10–15 m and at very low power levels. There are two different specifications for UWB systems in the IEEE 802.15.3a proposals, namely the impulse radio (IR-)UWB and multiband (MB-)UWB. Both IR- and MB-UWB systems are designed for indoor channels with long delay spread, which is also very common in intra-vehicle scenarios. In addition, UWB radios have several unique advantages, such as enhanced capability to penetrate obstacles, localization precision down to the centimeter level, very high data rates and high user capacity, small latency, and potentially small device size and low processing power [14]. The advantages of UWB open a door for high data rate applications in ITSp.

However, extensive research is still needed for intra-vehicle UWB because the original UWB systems were exclusively designed for inside-the-building environments while the intra-vehicular scenarios can be significantly different. Moreover, intra-vehicle UWB channels are significantly affected by the sensor node placement and vehicle parameters such as size, type, and even the window status. Although there have been some publications on the intra-vehicle UWB channel modeling and analysis with different settings, there still lacks a widely accepted channel model accommodating various intra-vehicle environments.

In addition, very limited media access control (MAC) sublayer research has been carried out for intra-vehicle UWB up to date, though MAC plays a key role in throughput and, more importantly for ITSp, latency. Currently, the IEEE MAC sublayer proposal for UWB, namely IEEE 802.15.3a, adopts the carrier sense multiple access/collision avoidance (CSMA/CA) technique, which may cause significant latency. In many cases, the wireless links in an intra-vehicle ITSp have very strict latency requirements, especially for safety-related information. Hence, real-time MAC protocols for intra-vehicle UWB could be an emerging hot research area.

60 GHz Millimeter Wave Technology — Another promising candidate for high data rate intra-vehicle wireless connections is millimeter wave at the 60 GHz ISM band. The Federal Communications Commission (FCC) allocated the 57–64 GHz band for the ISM unlicensed use in 2001. This 7 GHz bandwidth might give a relief to the bottleneck of wireless transmission by supporting data rates above 1 Gb/s. As millimeter waves at 60 GHz attenuate rapidly in air and can hardly penetrate obstacles, they are mostly considered for short range wireless transmissions such as personal area network (PAN) (e.g., IEEE 802.15.3c) and indoor wireless local area networks (LANs). Although intra- vehicle communications fall within the category of short range communications, research in this area is still very limited. In recent years, as rapid progresses are being made in electronic circuits, many 60 GHz transceivers and devices in CMOS and SiGe BiCMOS have been reported. The 60 GHz millimeter wave technology will attract increasing interests as the need of intra-vehicle communications increases.

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COMMUNICATIONS FOR VEHICLES, TRAFFIC, AND BEYOND

The communications among roadside infrastructures, traffic management centers, and other stationary nodes at fixed locations can be readily achieved with existing technology, such as optical fibre. One of the challenging yet critical issues in ITSp is the vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. Due to the vehicle mobility and the special requirements of traffic related information, we are faced with doubly-selective fading channels in both delay and Doppler domains, the hidden terminal problem, stringent maximum delay allowance, and reliability concerns. To overcome these challenges, the currently proposed V2V and V2I communication methods include existing technologies originally designed for other wireless scenarios, amendment to existing protocols, and approaches that start from scratch.

EXISTING TECHNOLOGIES

Similar to the intra-vehicle scenarios, existing technologies are the first being considered as potential solutions for V2V and V2I communications. Actually, the four technologies mentioned for intra-vehicle ITSp, namely Bluetooth, ZigBee, UWB, and millimeter wave communications, have all been considered for V2V and V2I communications. However, things are quite different here for the V2V and V2I scenarios. First, technologies for indoor or PAN scenarios are not designed to handle the Doppler introduced by moving vehicles. Secondly, the transmission range of these technologies does not meet the requirement of V2V and V2I scenarios. The transmission ranges of Bluetooth, Zig-

Bee, and UWB are all below 100 m, typically 10 m. For V2V cases, short transmission range means high vehicle density requirement that may not be met on highway or in rural areas. For V2I, short transmission range implies more roadside infrastructures and thereby increased cost. Thirdly, millimeter wave communications are typically designed for line-of-sight (LoS) links, which are likely unavailable in many V2V and V2I scenarios. As a result, the application of Bluetooth, ZigBee, UWB, and 60 GHz communications for V2V and V2I is limited only to some special cases. For example, these technologies can be used for V2V and V2I communications in a traffic jam where the vehicles are not moving and are very close to each other.

The most important reason to develop IEEE 802.11p based on IEEE 802.11a instead of starting from scratch is that IEEE 802.11a is a mature and stable standard that has been implemented in real applications for years and has strong industry support.

Another category of candidate for V2I communications is digital media broadcasting (DMB) systems, which include digital audio broadcasting (DAB), digital video broadcasting (DVB), and the standards by Advanced Television Systems Committee (ATSC). These DMB systems can cover a broad range with high data rates. For example, digital video broadcasting-terrestrial (DVB-T) covers over 40 km and ATSC terrestrial has a data rate of 19.39 Mb/s. However, all these DMB systems are based on single-frequency networks (SFNs) and can only be used for broadcasting. In other words, they may only be suitable for the scenario where the infrastructures are transmitting the same information to all vehicles in a mass geographical area.

Cellular systems such as Universal Mobile Telecommunications Systems (UMTS) are also promising candidates for V2I communications. UMTS account for the mobility in its protocol design and provide reasonably high data rates of up to 21 Mb/s with high speed downlink packet access (HSDPA), and possibly up to 100 Mb/s for downlink and 50 Mb/s for uplink as planned in the UMTS long term evolution (LTE). The estimated coverage range of the UMTS system is about 3 km. Cellular systems can provide two-way V2I communications with a star network topology, but still cannot support V2V communications that are essential for many applications in ITSp, such as vehicular ad-hoc networks (VANETs) and vehicular mesh networks.

WIRELESS ACCESS IN VEHICULAR ENVIRONMENTS

In order to overcome the challenges and to provide reliable wireless links for ITSp, new V2V and V2I technologies are necessary. In 1997, the Intelligent Transportation Society of America (ITSA) petitioned the FCC for a bandwidth of 75 MHz to support dedicated short- range communications (DSRC) for ITS. The FCC granted the DSRC band of 75 MHz from 5.85GHz to 5.925 GHz in October 1999. The ITSA recommended a single standard for the physical layer (PHY) and MAC, and proposed one based on IEEE 802.11. In 2004, IEEE task group p (TGp) of the IEEE 802.11 working group started IEEE 802.11p, an amendment to the IEEE 802.11a standard, to accommodate V2V and V2I communications. IEEE 802.11p defines the PHY and MAC. Additional layers in the protocol are covered by IEEE 1609.x that was released in 2006. IEEE 802.11p and IEEE 1609.x together compose the so-called wireless access in vehicular environments (WAVE) standards.

PHY — At PHY level, the IEEE 802.11p design is to make minimum changes to IEEE 802.11a OFDM PHY so that WAVE devices can communicate effectively among fast moving vehicles in the roadway environments. The most important reason to develop IEEE 802.11p based on IEEE 802.11a instead of starting from scratch is that IEEE 802.11a is a mature and stable standard that has been implemented in real applications for years and has strong industry support. To cope with longer delay spread in V2V and V2I channels comparing to that in indoor ones, IEEE 802.11p PHY uses 10MHz bandwidth instead of the 20MHz used by IEEE 802.11a. The implementation of this change is straightforward since it mainly involves doubling all OFDM timing parameters used in 20MHz IEEE 802.11a systems. The IEEE 802.11p PHY has an operation range of up to 1000m, which exceeds that of IEEE 802.11a, and provides data rates from 3Mb/s with BPSK to 27Mb/s with 64QAM. This relatively long transmission range guarantees V2V connections in urban and rural scenarios with different vehicle densities, and avoids constructing a large number of roadside infrastructures.

Channel Characteristics and System Implementation — To design IEEE 802.11p receivers and evaluate the performance, knowledge of the channel characteristics is essential. Therefore, in recent years, as the IEEE 802.11p approaches its release date, DSRC channel measurements have attracted much attention. Existing work reveals that the fading becomes more severe as the distance increases, from a near-Rician fading at a short distance of several meters to a pre-Rayleigh fading at a long distance of hundreds of meters. The Doppler spread and coherence are both velocity and vehicle distance dependent. In addition, The joint Doppler-delay power spectrum density (PSD) measurements with a 10 MHz IEEE 802.11p bandwidth were carried out in different scenarios in the existing work. The maximum delay spread measured is around 700 ns. That means the 1600 ns OFDM guard interval in IEEE 802.11p PHY is more than sufficient. Moreover, the measured joint Doppler-delay PSD varies significantly in different scenarios. Interestingly, the Doppler measured PSDs for V2V and V2I communications vary from scenario to scenario, but most of them are quite different from the traditional bowl-shaped PSD for Rayleigh fading channels with rich scattering reflections from all directions. More existing research work on V2V and V2I channels is found in a survey [15]. These phenomena indicate that there should not exist a universal channel statistics model for different scenarios and more research efforts should be devoted in order to reveal more between the channel statistics and the different V2V and V2I scenarios.

Although there are no commercial products based on IEEE 802.11p, the implementation of the protocol is attracting many interests. The most significant challenge in implementing IEEE 802.11p, comparing to traditional IEEE 802.11a, comes from the doubly-selective fading V2V and V2I channels. This double selectivity challenges the IEEE 802.11p receiver design, especially channel estimation and equalization since OFDM is originally designed for time-invariant channels. Some possible solutions such as inserting extra pilot OFDM symbols and taking advantage of the cyclic prefix have been reported. These methods either introduce extra overhead or are limited by the channel delay spread. There are still more research efforts needed in this area and still other methods potentially feasible, such as tracking.

MAC — The IEEE 802.11p MAC is also an amendment based on that of IEEE 802.11a. In IEEE 802.11a MAC, an access point (AP) sends beacons periodically as an advertisement. A node first listens to the beacons and then joins the basic service set (BSS) through a number of interactive steps. However, vehicles have high mobility on the road and thereby the iterative steps for the node to join the BSS in IEEE 802.11a become unaffordable for the V2V and V2I scenarios. IEEE 802.11p MAC addresses this problem effectively. A WAVE station does not send beacon periodically but uses an on-demand beacon that contains all information for the receiver to decide whether to join. As a result, a node can join the WAVE BSS in just a single step. This nice one-step joining property fulfills the quick networking setup requirement in vehicular ad-hoc networks (VANETs) that provide many applications in ITSp, such as group information sharing, collision avoidance, and platoon autonomous driving.

Another standard in WAVE, IEEE 1609.4 provides enhancements to the IEEE 802.11p MAC by supporting multichannel operation. There are seven 10MHz channels in the DSRC band. Channel 178 is reserved as the control channel (CCH), which supports high power levels and is solely broadcasting safety-related information, vehicle control commands, and other messages with high priority. The other 6 channels are service channels (SCHs) conveying information for other services. Moreover, the WAVE MAC adopts enhanced distributed channel access (EDCA) with quality of service (QoS) support. The messages are divided into 4 access categories (ACs) with different priorities. However, all these still only partly meet the needs for the various applications in ITSp. The main reason is that the WAVE MAC protocol still relies on CSMA/CA that provides nondeterministic channel access and thereby is not hard realtime. Some applications in ITSp, including collision avoidance and autonomous driving, require hard realtime information delivery. Under dense traffic conditions, even the safety-related time-critical message dissemination cannot be guaranteed because of the increasing packet loss and average delay.

OTHER MAC PROTOCOLS

Besides the WAVE MAC that is an amendment to the CSMA/CA based on IEEE 802.11a, extensive research has been carried out to develop new V2V and V2I MAC protocols from scratch based on other multiple access techniques to avoid the packet congestion problem inherent to CSMA/CA. These MAC protocols are based on frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). FDMA and TDMA are promising categories of MAC protocols ensuring short and bounded latency. Hence, they are suitable for applications with critical delay requirements. However, it is difficult to dynamically generate and update the frequency subband or time slot assignment as the vehicles join and leave.

The MAC protocols based on CDMA can be regarded as an extension of cellular systems since CDMA is traditionally adopted in cellular systems with centralized code assignment and precise synchronization. Although the CDMA based MAC protocols are expected to have small latency as the CDMA cellular systems, both code assignment and synchronization become challenging in VANETs due to the lack of a centralized structure. In addition, most of these protocols improve one aspect at the cost of others [16, references therein]. For example, some protocols improve the QoS of safety-related applications by sacrificing considerable bandwidth resource for general services. As a result, despite the extensive existing work, V2V and V2I MAC remains an intriguing topic requiring considerable research efforts.

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CONCLUDING REMARKS

ITSp are intelligent spaces integrating multiple ITS modules as well as the participants and devices in transportation. With their interlaced cyber, physical, and social aspects, ITSp are expected to bring transportation safety, efficiency, and comfort to another level. To realize the distributed and pervasive intelligence of ITSp, communications and networking are clearly key enablers. This article elaborated on the potential wireless communication technologies for ITSp. We presented a number of currently developed technologies that have some suitable characteristics for ITSp, and illustrated the state of the art of some technologies under development. From the discussions in this article, it is clear that one technology only fits some certain applications and it is envisioned that ITSp will adopt multiple communication technologies and standards.

In this article, we mainly focused on the lower layer issues of the wireless communication technologies, including transmission power, bandwidth, data rate, channel characteristics, PHY receiver design, device wakeup latency, and media access latency. In addition to these issues, higher layer concerns such as routing and security are also important and challenging. These topics have attracted increasing interests lately. Examples include geographic routing [17] and multipath routing [18] for VANETs. In ITSp, the consequences of malicious intrusions to safety- related applications could be fatal. In WAVE, security services are defined in IEEE 1609.2. Additional research on this topic can be found in [19, references therein].

The realization of ITSp is challenging, time-consuming and effort-taking. However, one does not have to wait till its full realization to benefit from ITSp. In fact, current ITS can be regarded as a series of independent small-scale ITSp that fulfill some specific needs. Moreover, the concept of ITSp, where all participants in transportation are connected and managed by intelligent nodes, enlightens the design of future personal devices, vehicles, roads, and transportation systems as well as many other cyber-physical-social systems [10].

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