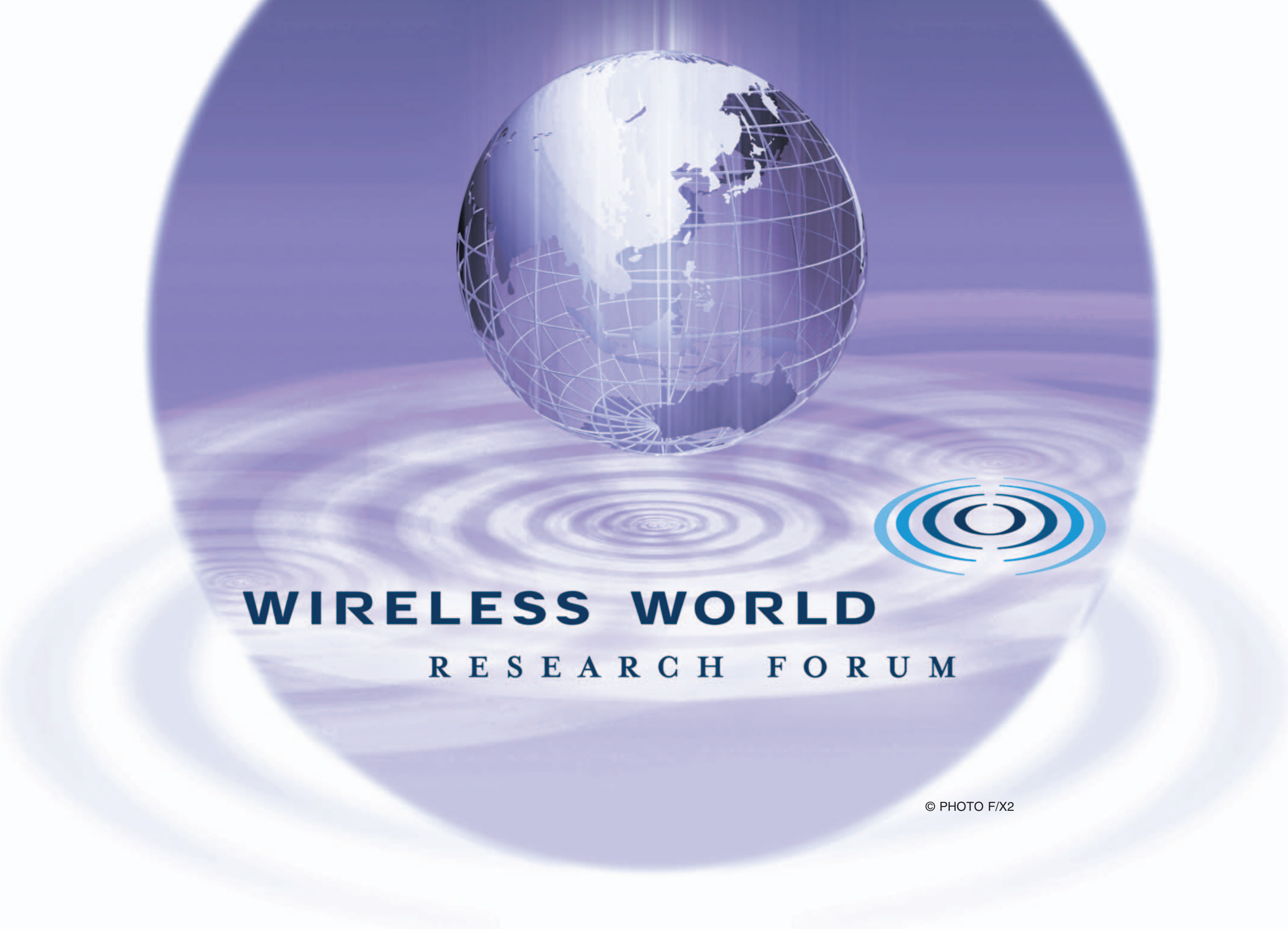

CAR-2-X AND PEDESTRIAN SAFETY

Innovative Collision Avoidance System

Klaus David and Alexander Flach

Traffic accidents involving pedestrians or cyclists cause thousands of fatalities and serious injuries every year. In this article, we present an innovative approach for a collision avoidance system that seeks to reduce these accidents. We also discuss the different architectural approaches utilizing ad hoc and/or cellular technologies and different processing setups and present a physical analysis of the system time available between detection, warning, and reaction to give an overview of the time constraint.

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Official figures of the global comparison presented in [1] show that every year more than 400,000 pedestrians worldwide are killed in traffic accidents. To address this problem theoretically, the following needs to be done: First, an overview of the scenario is required (car, pedestrian, street, other pedestrians, etc.); second, we have to have an approach, i.e., a filter, to identify the pedestrian (out of potentially many) who collides with the car; third, a way to communicate this information to the right entity; and finally, trigger appropriate action (such as warnings or more).

Obviously, not all car–pedestrian accidents can—even in principle—be avoided. For example, a car is passing by

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at 50 km/h and a pedestrian happens to step onto the street less than 1 m in front of the car: unfortunately, we are not aware of any solution to avert a collision.

Nevertheless, pedestrian safety is a subject of increasing interest and investigation, and there are currently two main approaches to prevent the accident. First, passive pedestrian protection—by designing the bumper and other critical parts of the car in such a way that, in case of collision with a pedestrian, the potential harm will be reduced as much as possible—even air bags are under consideration. Second, research is being done in active pedestrian protection, such as pedestrian detection, collision warning, and automatic braking. Since most of the accidents involving pedestrians occur in urban areas, the different approaches are aiming at urban accident scenarios like the one shown in Figure 1. Consider a typical scenario where a car is driven at a speed of 50 km/h and a pedestrian is setting out to cross the street through the gap between the parked cars. The pedestrian is not visible to the car driver and is not aware of the approaching car. Only when the pedestrian steps onto the street does he become visible to the car driver.

At this point, it might already be too late to react and so the potential of the accident is high. This accident scenario is typical of many, and this includes cyclists as well.

To address these accidents, various R&D groups are working on approaches that can be categorized as follows:

- video analysis based on visible and
- nonvisible light (like infrared)
- radar based
- laser distance measurement
- tag-based approaches.

See [2] for more information. All but the last approach need a line of sight to work properly. If the pedestrian is only partially visible, not visible at all, or if there is insufficient contrast between the pedestrian and the surroundings, the system may not work properly or may fail altogether.

Tag-based approaches as described in [3] and [4] use radio frequency identification (RFID) tags fixed to the pedestrian and a transmitter/receiver device mounted on the car to detect the position of the pedestrian and make predictions of the next movements. These systems do not need line of sight but have a very limited communication radius. The approach described in [3] and [4] helps in detecting pedestrians for up to 60 m. This promising approach needs no line of sight but has a limited maximum communication radius, requires additional equipment to carry, and offers little information about the pedestrian, and therefore, advanced filtering might be difficult if not impossible.

In summary, an optimal system is very hard to achieve or even impossible because of the necessity of line of sight, having little or no information about the agility of the pedestrian (age, weight, height, etc.), unavailability of additional context information (tired, being in a hurry, planning to take the tram, etc.), and the movement pattern of the last few seconds.

The rest of this article is organized as follows: The "Radio-Based Collision Avoidance System" section gives an overview of our approach. In the "Radio Communication and Processing Architectures" section, different architectural approaches are discussed. A physical analysis of the accident scenario above, describing the dependencies of different parameters influencing the system time available for a collision avoidance system is given in the "Physical Analysis of an Accident Scenario" section. The "Time Delay Measurement Results" section presents the results of our experimental measurements of connection establishment times and ping response times within ad hoc and cellular networks to investigate if these radio communication technologies are candidates for implementing a collision avoidance system. The "Filter and Next Steps" section presents the first results about the filter. Finally, the conclusions are given.

Radio-Based Collision Avoidance System

A radio-based collision avoidance system does not need line of sight for communication and can obviously be built on an almost universal available infrastructure of global system for mobile communication (GSM)/universal mobile telecommunications system (UMTS). The approach presented in [5] uses global positioning system (GPS)-based positioning data exchanged via UMTS between a pedestrian's mobile phone, a car's navigation system, and a central server. This server estimates the risk of a collision with the help of positioning data and additional information (which is not specified in detail in [5]). The result is sent to the mobile phone and the navigation system of the car. In case of high accident potential, the risk estimation is sent to the car and to the pedestrian's mobile phone, and a direct communication between the car and the mobile phone of the pedestrian based on wireless local area network (WLAN) is established to exchange further positioning information.

Our approach to a collision avoidance system presented in [6] has a very similar vision as the approach presented in [5]. We assume that the position information of the pedestrian as well as of the car is given with sufficient precision, e.g., covering a range from 10 to about 80 cm, either by GPS or Galileo or another positioning approach. This position information will be available to the collision avoidance system which runs, depending on the architecture on a mobile

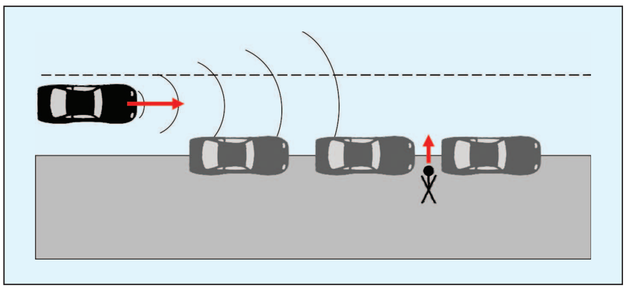

FIGURE 1 Typical accident scenario with the radar as pedestrian detection.

phone of the pedestrian, in a car system, and/or on a central server. Furthermore, context information and an extended information set, i.e., the pedestrian's personal profile, can be available for use by the collision avoidance system for an intelligent filter. The personal profile can contain information about the pedestrian, such as age, maximum speed and acceleration, personal calendar, etc., as well as movement history, and the current speed and direction. When a car enters within a certain distance to the pedestrian, the personal profile can be exchanged with the help of radio communication technologies. The exchanged position as well as context information is used by the filter mechanism to calculate the risk of a collision. If the risk of a collision is estimated as high, a warning is sent to the car driver and/or the pedestrian.

Among others, two basic functions have to be supported by the architecture: the communication of the relevant information and the processing of this information. For the communication, three architectural approaches are possible (see Figure 2):

1) communication based on existing cellular networks such as GSM/general packet radio service (GPRS) enhanced data rates for GSM evolution (EDGE) or UMTS/high speed packet access (HSPA)/long-term evolution (LTE) given by the discontinuous dark red line in Figure 2
2) based on ad hoc infrastructure-less communication based, e.g., on WLAN (or variants of WLAN such as IEEE 802.11p [10]), ZigBee, or other ad hoc air interfaces given by the discontinuous blue line in Figure 2
3) a hybrid approach that is based on cellular as well as ad hoc networks.

In addition to the communication possibilities above, the processing of the filter can, in principle, happen to be in the three entities or distribution between these entities which are as follows:

1) the mobile phone
2) the car
3) a central server.

In the next section, the different approaches and combinations will be discussed in more detail, including the discussion about the potential advantages and disadvantages.

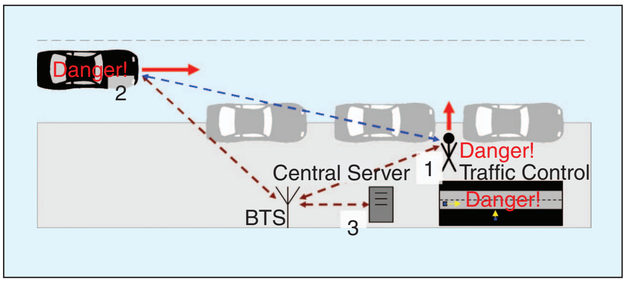

FIGURE 2 Collision avoidance system based on ad hoc and/or cellular networks.

Radio Communication and Processing Architectures

The different architectural possibilities are quite numerous. There are different combinations using ad hoc and cellular networks for the setup in Figure 2 with pedestrian, car, and central server:

1) having the communication between the pedestrian's mobile phone and car via ad hoc networks, the pedestrian and central server via cellular networks, and the car and central server via cellular networks
2) having the communication between the pedestrian and car using cellular networks, the pedestrian's mobile phone and server, and the car and the central server using cellular networks.

Without using a central server, there are two additional combinations, i.e., communicating via cellular or ad hoc. All these combinations we do have again in a system chooses the communication architecture dynamically. Together with the different processing setups, there are quite a few possible combinations. To find the most suitable of these combinations, we use the following four criteria:

1) energy consumption of the mobile phone, because we do not want to change the pedestrian's usage of the mobile phone as the battery runs low very quickly when using the collision avoidance system
2) time agility, i.e., how much time the system has between sensing and reaction; important contributions to this are ping response time and connection establishment time, processing power for filtering, number of additional transmissions, and communication radius
3) reliability of the architecture where challenges are caused by transmission failures, broken connections, or part of the architecture not functioning
4) cost, central backup, time needed for deployment, and influence to the filter algorithm.

One architecture candidate is based on ad hoc networks having a direct connection between the car and pedestrian. The energy consumption on the mobile phone is higher compared with using cellular networks. Furthermore, only two processing entities are available, the mobile phone of the pedestrian and the car. If processing is done on the mobile phone, the energy consumption is even higher. Time agility is good in terms of ping response time, but the connection establishment time as well as limited communication radius has to be considered. No base stations are required, so fewer points of failure exist, but the communication itself including the setup is not reliable. The system is easy to deploy as no base stations are needed for communication, but as there is no central server available, no central backups or central processing can be done. The different views, ranked from the best as $++$, good $+$, medium 0, bad $-$, and very bad $--$ for the ad hoc setups are shown in Table 1.

For the architectural candidate where only cellular networks are used, the energy consumption on the mobile phone may be less compared to using ad hoc networks, especially if there exist a good coverage of base stations, and instead of using the mobile phone for processing, a central server is used, if available. The communication radius in ad hoc technologies typically limited to at most a few hundred meters and in cellular networks is quite large. The processing power in a central server can be dimensioned to the system's needs. The ping response time is not as good as ad hoc networks but still sufficient. The communication itself is reliable, but quite a few points of failure exist like base stations and the underlying network. Single points of failure can be affected by installing redundant central servers or by using other base stations, but still the system might fail as a cause of power loss. The investment and operational costs of using cellular networks are higher compared with a solution based on direct ad hoc communication. Base stations need power, service, and if there is only poor coverage or no coverage at all, base stations and infrastructure have to be installed. An artificial filter is needed to show and consider only pedestrians who are near because of the large communication radius available. Central backup and the possibility to have a central overview over places of high accident potential is also available in a cellular network-based solution. An overview of the criteria and processing setups in cellular networks is shown in Table 2.

As described above, neither solution seems to be the only or best solution. A hybrid solution that is able to choose the most suitable way of communication and processing setup based on the availability, usage, and context is our favorite. This choice incorporates the advantages of both solutions.

TABLE 1 *Criteria view for ad hoc networks and processing setups.*

Communication Architectures and Processing Setup Combinations	Ad Hoc		
Location of the Filter Processing	Car	Mobile Phone	Car, Mobile Phone
Criteria			
Energy consumption	+	−−	−
Time agility	−	−	−
Reliability	−	−	−
Other	0	0	0

Physical Analysis of an Accident Scenario

In this section, we will present a physical analysis of an accident scenario that is presented in a more detailed view in [6]. The time available for detection of a car/pedestrian, transmission of data, calculations, and warning to make the driver/pedestrian aware of dangerous situations to avoid a collision, i.e., the system time available t_{sta} is determined by the speed of the car v_{car}, the deceleration a_{car} of the car, and the communication radius s_{com}:

$$t_{\mathrm{sta}} = \frac{\left(s_{\mathrm{com}} - \left(v_{\mathrm{car}}^2/2a_{\mathrm{car}}\right)\right)}{v_{\mathrm{car}}} - t_{\mathrm{rea}}. \qquad (1)$$

Without loss of generality, the speed of the pedestrian is assumed to be zero here.

- s_{com}: the communication radius is the distance up to which the mobile phone of a pedestrian and a communication device of a car are able to communicate with each other. If cellular networks are used for communication, the communication radius is then virtual and can be set to have a first spatial filtering for detecting only pedestrians who are close.
- a_{car}: the deceleration of the car is calculated by $a_{\mathrm{car}} = v_{\mathrm{car}}^2/2s$, with s being the braking distance from the initial speed to 0 happening in the braking time t_{bra}.
- t_{rea}: driver's reaction time which is the time between the occurrence of an event and the driver's reaction and the time taken up by the brakes' response to the driver's action. The studies in [7] and [8] analyze this topic by means of experimental measurements and give an average reaction time of a driver to be 0.63 s. The average response time of the brakes is given to be 0.2 s. Added together, 0.83 s is the average time between the occurrence of an event and the start of the car's braking process. This average value is used in our analysis throughout this article.

If the system time available t_{sta}, the time for reaction of driver and brakes t_{rea}, and the time for braking t_{bra} are added together, the result is the total time t_{tot}, which is the time available in the communication radius s_{com}.

Dependency Between a_{car} and t_{sta}

Improvement of brakes can help to avoid collisions and to increase t_{sta}. The t_{sta} is less in a scenario of a car decelerating with 8 m/s^2 compared with a car decelerating with 11 m/s^2 and is 0.2 s at a speed of 50 km/h and 0.4 s at a speed of 70 km/h for the communication distance of 50 m.

TABLE 2 *Criteria view on cellular networks and processing setups.*

Communication Architectures and Processing Setup Combinations	Cellular						
Location of the Filter Processing	c	m	cs	c, m	m, cs	c, cs	c, cs, m
Criteria							
Energy consumption	++	−	++	−	−	++	0
Time agility	+	+	+	+	+	+	+
Reliability	−	−	+	+	+	+	+
Other	0	0	++	+	+	+	+

c: car; cs: central server; m: mobile phone.

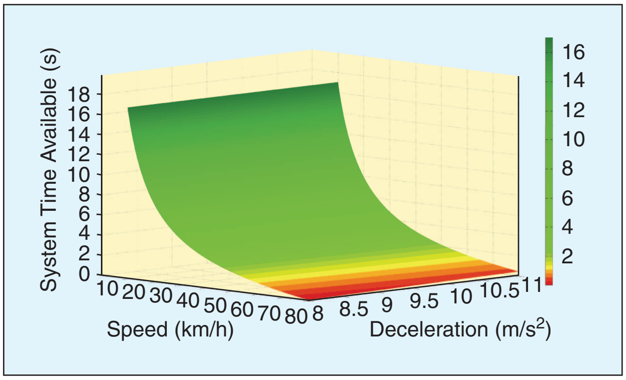

FIGURE 3 System time available t_{sta} as a function of v_{car} and a_{car}.

The dependency between t_{sta} and deceleration is linear, which can also be seen in Figure 3.

Dependency Between s_{com} and t_{sta}

The dependency between s_{com} and t_{sta} is linear as well. because it is the result of the constant v_{car} with which the car covers distances larger than the braking distance, which in our case is 9,725 m at a speed of 50 km/h and deceleration of 10.4 m/s^2.

Dependency Between v_{car} and t_{sta}

Another parameter influencing t_{sta} is v_{car}. The increase of v_{car} causes a quadratic increase of the braking distance and decreases the time needed to cover a distance. The result of increasing v_{car} is presented in Figure 3 as well as the information at which t_{sta} is going to be 0 s. The chosen a_{car} in this diagram is between 8 and 11 m/s^2 and s_{com} is 50 m. The figure shows the decrease of t_{sta} for increased speeds, being the result of two influencing components: the decreased time to cover a certain distance and the increase of the braking distance. The t_{sta} decreases, for example, for $a_{car} = 10.4$ m/s^2 and $s_{com} = 50$ m from 6.1 s at 25 km/h to about 2.1 s at 50 km/h and to about 0.8 s at 70 km/h. At a speed of about 90 km/h, t_{sta} is 0 s, meaning that there is not more time available for a collision avoidance system for the chosen scenario parameters.

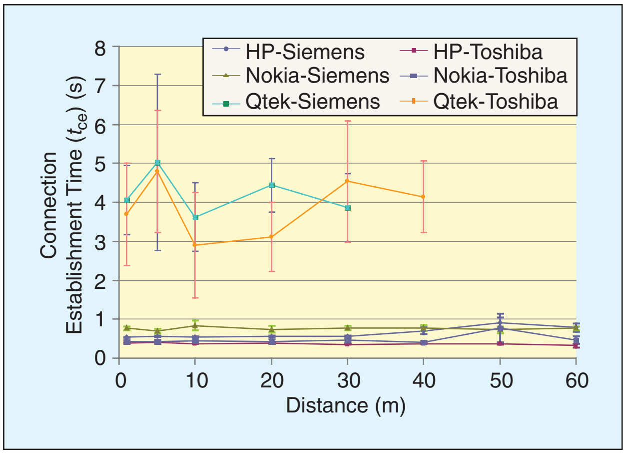

FIGURE 4 Connection establishment time (t_{ce}) in ad hoc networks.

If s_{com} is extended to 100 m, $t_{sta} = 5.6$ s. As we will also verify with the practical measurements in the next section, we strongly believe that the system time available for about 2 s gives sufficient time for the realization of functioning, real systems. In addition, with 2 s, more time is available than with the radar, video, and laser-based approaches discussed in the state of the art.

Time Delay Measurement Results

To relate our physical analysis given above with real wireless systems, we present measurement data in this section. To obtain the first evaluation regarding the feasibility of such a collision avoidance system, we present the measurement data of currently available systems. We use currently available products, specifically IEEE 802.11b [10], GPRS, EDGE, UMTS, and HSPA. It can be expected that future standards such as IEEE 802.11p or LTE will be even better concerning low latencies.

Ad Hoc Architecture Measurements

For the measurements, we have used the following devices:

- personal digital assistants (PDAs): HP iPAQ H4150
- smartphones: Qtek 8310, N95
- laptops: Toshiba M200, Siemens Lifebook C1320.

The PDA and smartphone are typical mobile phones. We made measurements with all combinations of devices connected to laptops for communication radii up to 60 m.

First, we consider the time needed to establish a connection in ad hoc networks between the communication devices before the data can be exchanged. The time between one communication device entering the communication radius of another device and a connection being established is referred to as connection establishment time (t_{ce}).

The different devices show that there is quite a variation for the t_{ce}, as shown in our measurement results, see Figure 4. For some that would be suitable for our application, it is less than 1 s, for others ≅4 s. The variation due to distance is negligible.

Second, to get an estimation about the time needed for data exchange between the communication devices, we have sent ping packets giving the minimum round trip time for data exchange. The measured ping response times (t_{pr}) for communication radii up to 60 m are shown in Figure 5.

To represent some information of the personal profile to be sent, we chose 50 B for the size of the ping packet. Again, there are variations between different devices. Nevertheless, even for the worst result of 16 ms, with the overall system time available of 2 s, from which we have to subtract 1 s of t_{ce}, gives us the possibility of having more than 60 ping responses within the time constraints.

Cellular Architecture Measurements

For cellular networks, we can assume $t_{ce} = 0$ s, because the use of cellular networks allows for the assumption that both the pedestrian and the car have established a cellular connection. We used an HP Pavilion ze2000 laptop and Novatel Wireless Merlin U530 GPRS/ UMTS PCMCIA card for GPRS and UMTS, a Nokia N95 for HSDPA 3.6 Mb/s and UMTS for the uplink, and a Huawei E870 PCMCIA card for HSPA measurements (7.2 Mb/s download, 2 Mb/s upload, respectively.) We made t_{pr} measurements to different servers to get data independent of server response time characteristics (see Figure 6).

GPRS has a maximum t_{pr} of about 600 ms, UMTS of about 200–300 ms, HSDPA (N95) of about 140 ms, whereas HSPA as the latest cellular network has a delay of about 100 ms.

The ping times as such are one order of magnitude larger than for WLAN. Nevertheless, the overall time balance for HSPA, e.g., will still allow for about 20 pings for the time constraints of 2 s, because here the connection establishment time is 0.

The results supporting our measurements are shown in [9]. Differences in [9] are inclusion of fast-moving mobiles up to 100 km/h and the usage of car roof antennas. With the help of the physical analysis and the practical measurements we did, we have shown that our approach of a radio communication-based collision avoidance system between cars and pedestrians presented here is feasible based on the chosen scenario parameters. The remaining time for collision avoidance may even be increased by expanding the communication radius if cellular networks are used or by optimized radio communication technologies available in the future.

Filter and Next Steps

The development and evaluation of an enhanced filter mechanism used to find the pedestrian who might cause a collision and not all pedestrians present, see Figure 7, is one of the next key parts and steps of the approach presented here and in [5]. There are different filter algorithms possible dependent on the available information.

Simple filters could function as follows.

- Provided the movement direction is known, all pedestrians not moving in the direction toward the street are filtered out. This would of course mean that quite a few pedestrians still have to be considered after filtering, so the goal of having identified the pedestrian after filtering will not be possible.
- The position and the typical maximum speed of a pedestrian is used to calculate whether the pedestrian will reach the street before the car passes him.

Even these simple filters show a substantial improvement in comparison to the first four approaches given in the introduction. This is because these five approaches required line of sight between the pedestrian and car. For our scenario, these systems could only react when the pedestrian was already on the street, whereas our system approach with the filters above is already working vitally important seconds before this point in time.

Through this approach, we can create more sophisticated filters that can be based on different informations such as

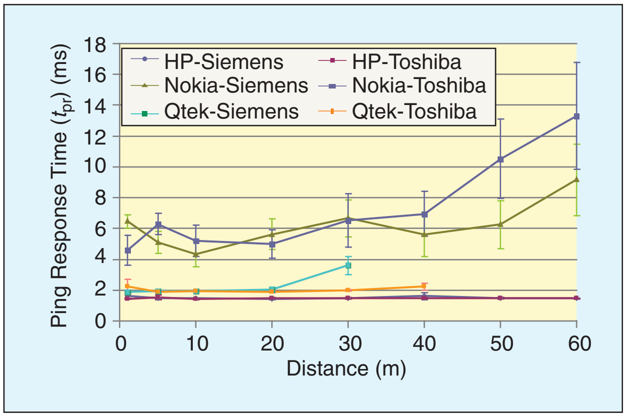

FIGURE 5 Ping response times (t_{pr}) WLAN, different distances, and different combinations of communication devices.

- movement history
- personal profile consisting of agility, including maximum speed and acceleration of the pedestrian
- context of the pedestrian-like activity, e.g., talking on the phone, reading text messages, surfing the Web, etc.
- personal calendar
- high risk locations like bus stops and schools
- the current speed and direction.

A sophisticated filter has a system that predicts that the pedestrian is not able to walk quickly or to run, e.g., the distance covered by the elderly per second is considerably shorter than for young people. Therefore, this

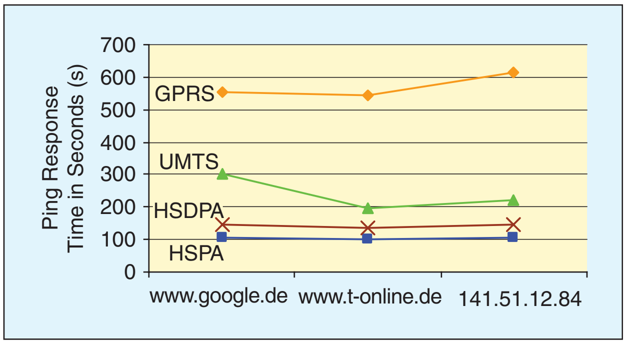

FIGURE 6 Ping response times (t_{pr}) for cellular networks.

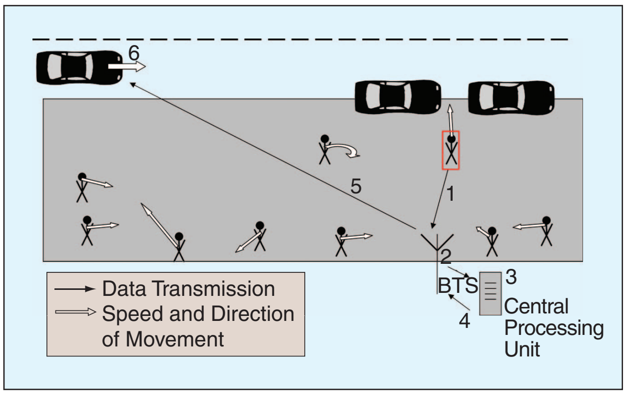

FIGURE 7 Example of a filter schema.

pedestrian may walk closer to the street and cannot reach the street before the car passes him. Another sophisticated filter could use the pedestrian's movement history to identify typical movements, e.g., drunk pedestrians. To develop and evaluate the different filter algorithms is one of the next steps of our work.

The investigation presented here has shown that the timing constraints are tight, but we are convinced that it should be possible to handle them. For a further evaluation of our innovative approach, further investigations, especially of the filter and its timing demands and of the influence of position inaccuracy, are required. Evaluating the different communication architectures to find the most suitable communication architecture is also necessary. The following questions need to be addressed: which communication architecture has which capacity to handle what amount of users to be answered, as well as which data are useful for a personal profile, which data format can be used, and what is the most suitable solution to ensure data security. The research of optimization of the different communication technologies for minimum power consumption, delays, and communication setup times, as well as battery time of mobile phones, are important parameters influencing the design and choice of the architecture.

Conclusions

We have presented an innovative Car-2-X system concept for pedestrian safety. It is based on detection, filtering supported by personal profiles and context awareness, prediction calculation, communication, and warning. The different architectures consisting of ad hoc and/or cellular networks for communication and the processing setup for filtering were discussed. For the criteria discussed—energy consumption of the mobile phone, time agility as well as reliability of the system, and other considerations—a hybrid solution that is able to choose the most suitable way of communication and processing setup based on the availability, usage, and context is the most promising architecture.

We have shown a comprehensive analysis of the timing constraints any working collision avoidance system has to stay within as one important prerequisite, considering the important parameters of communication radius, deceleration, and speed of the car, respectively. For a car driving with 50 km/h, a deceleration of 10.4 m/s^2, a reaction time of 0.83 s, and a communication radius of 50 m, the system time available is 2.1 s (for 100 m it is 5.6 s).

As confirmed by measurements, 2 s would be sufficient for a nonlatency-optimized ad hoc system using IEEE 802.11b to include the connection establishment time [about 1 s and still being able to have several tenth of profile exchanges (each one lasting about 2 ms)]. Also confirmed by measurements, e.g., HSPA with a round trip time of about 100 ms would allow for several loops of profile exchange.

The system approach presented here allows for context aware filtering to identify the pedestrian by using information about the agility of the pedestrian (age, weight, height, etc.), additional context information (tired, being in a hurry, planning to take the tram, etc.), and the movement pattern of the last few seconds. Despite the considerable challenge for such an approach, the results and issues discussed indicate the feasibility of our approach.

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Klaus David (david@uni-kassel.de) received both his diploma and Ph.D. degree in 1988 and 1992, respectively, from the University of Siegen, Germany. He has 12 years of industrial experience with Hewlett Packard (HP), Bell Northern Research, IMEC, T-Mobile (as head of group), and Innovations for High-Performance Microelectronics (IHP) (as head of department). He has more than 140 scientific publications, and since 1998, he has been a professor and, since 2000, the head of the chair for communication technology (ComTec) at the University of Kassel in Germany. His research interests include mobile applications and context awareness.

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