

A Mountain-Bike-to-Hiker Warning System (MBHWS)

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Abstract—This paper presents a novel application for V2X communication, namely a Mountain-Bike-to-Hiker Warning System (or short MBHWS) which should ease the ongoing conflict between hikers and mountain bikers in many alpine regions where both use shared trails. Fast approaching and overtaking bikers can scare hikers, especially when the latter do not recognize the bikers early enough, and in consequence conflict-ridden or dangerous situations regularly occur in mountains. Building on recent technology advances and inspired by recent works on Vulnerable-Road-User protection, we analyze the MBHWS use-case and its requirements, derive and implement a system design to show the general feasibility, conduct technical tests of the system prototype in a realistic outdoor environment in the Italian Alps, and also perform a user-study to analyze user acceptance and preferences. We conclude that a MBHWS is technically feasible based on widely available consumer-grade equipment and our user study gives indications about high user-demand and preferences of different user groups.

Index Terms—mountain biking safety; bike-to-pedestrian communication; vulnerable road-users; hiker warning system

I. INTRODUCTION AND MOTIVATION

Fueled by the increased popularity of outdoor sports during the COVID-19 pandemic and the increased availability of electric mountain bikes (eMTBs), recent years have seen a surge in popularity of mountain biking and this trend is predicted to continue with annual growth rates between 6 % to 9 % [1], [2]. In areas where no dedicated trails exist for mountain bikers and trails are thus shared with hikers, this increasingly creates conflicts with hikers sharing the trail. Those often feel annoyed or get scared by bikers approaching and overtaking them (in particular from the back). In the worst case, this can even lead to accidents and injuries. While a systematic assessment of this phenomenon is lacking, analyses from specific areas like Slovenia [3] or Australia [4] consistently indicate that this is a conflict that cannot be ignored but needs to be managed. While dedicated mountain bike trails and trail parks offer one avenue to reduce the conflict potential, in many areas this is not possible or wanted as it would consume additional space and create extra maintenance cost. Switzerland is one of the countries that has acknowledged the touristic and economical value of mountain biking and is actively building a large network of shared trails. At the same time, they are also requesting bikers to be considerate and give priority to hikers on shared trails [5]. In

other countries, the very same conflict leads to progressing legal bans of shared trail usage by bikers. Mitigating the conflict also by technical means could therefore contribute to keeping nature more accessible for use for recreational sports independent of moving on foot or wheels.

Our work is based on the assumption that one source of conflict are fast approaching and overtaking bikers who can scare hikers, especially when the latter do not recognize the bikers early enough, and in consequence conflict-ridden or even dangerous situation regularly occur in the mountains. This is in alignment with the findings of Zajc et al. [3] and corresponds with general perception in the news [6], [7]. In our scenario, a biker approaches a hiker from behind on a downhill slope and at significantly higher speed. The hiker does not notice the biker until the very last moment, i.e., when the biker passes him or her at substantially higher speed and at relatively short distance. Besides the unpleasant experience of being scared, the hiker may also show sudden reactions like stepping to the side, colliding with the biker or stepping off the trail. We postulate that early and unobtrusive warnings to hikers would defuse the situation substantially and result in much better coexistence of bikers and hikers on shared trails. There exist even low-tech solutions in the form of bells that a biker could mount on the handlebar to emit constant ringing sounds [8]. However, the constant sound might also be considered disturbing. In earlier research [9], we proposed a technically solution, leveraging information technology and wireless communication to produce a warning on a hiker's carry-on devices. But ultimately both approaches aim for the same goal.

While some popular biking apps for smartphones like Komoot or Strava already foresee a live tracking of a biker's position via cellular networks, this serves fundamentally different purposes (tracking your ride, informing your security contacts about your whereabouts, etc.) and is not directly comparable to the MBHWS.

In this paper, we extend this initial work with a more in-depth treatment of our Mountain-Bike-to-Hiker Warning System (MBHWS). To this end, we first present a detailed requirements analysis for our use-case in Section II followed by a system design and prototypical implementation to fulfill these requirements in Section III. Section IV then reports

on experiments we conducted for technical evaluation in realistic outdoor scenarios in summer 2024. Finally, Section V reports on the findings of a user study which we conducted to assess user demand, acceptance, and preferences. Section VI summarizes our results and provides an outlook into our ongoing work.

II. REQUIREMENTS ANALYSIS

As already described in Section I, our use-case foresees a biker overtaking a hiker from behind on a downhill slope, as depicted in Fig. 1.

In short, a biker B is approaching a hiker H on a shared downhill trail from H 's back. But even from the front such a situation can be dangerous if the hiker is not paying attention or arrives around a bend with poor visibility. The overall goal of our system is to transmit a warning to the hiker for increased awareness and timely reaction.

This warning needs to 1) reliably warn the hiker with sufficient time in advance to react, 2) provide an intuitive information to H about the remaining time until the biker might overtake, 3) be unobtrusive to avoid disturbing hikers unnecessarily during his recreational activity.

Likewise, a warning is also shown to the biker to make him aware and bike slower and more carefully.

To implement the MBHWS, B and H are each equipped with a telematics unit BT and HT that together implement the Mountain-Bike-to-Hiker Warning System (MBHWS).

The telematics units share a common design in that they need to have functional blocks implementing 1) communication to exchange necessary information, 2) a logic to calculate the distance between B and H or otherwise assess the estimated time-of-arrival (ETOA) that should then be reflected in the warning, 3) positioning to periodically measure the positions of B and H which can contribute to the calculation logic (optional), and 4) a suitable user interface to finally deliver a warning.

We now analyze requirements for system components and investigate existing technology options to implement them.

A. Hardware Platform

For the hardware platform, we identified the following requirements:

1) *Cost*: no extra cost for the hiker, limited extra cost if integrated into eBike; 2) *Portability*: for the hiker, device should be portable, for the biker, easy integration into or attachment to the bike would be preferable; 3) *Compute power*: both computational and delay requirements are not very stringent, consequently even low-performance micro-controllers should be able to implement the MBHWS; 4) *Battery capacity*: for the hiker, the battery capacity must at minimum support a one-day activity before requiring recharging. For the biker using a regular bike, the same applies as for the hiker; in case of an eBike, the bike's battery can provide sufficient power; 5) *Supported technologies*: the chosen platform must be able to support all further functionality (communication, positioning, user-interface) depending on the technologies chosen below.

We analyzed two possible hardware platforms. A *dedicated device* based on a common microcontroller platform (ranging from Arduino to Raspberry Pi) and a Smartphone-based app (potentially extended by a smartwatch app).

A smartphone is considered to be available and thus creates no extra cost and is carried by most hikers and bikers anyways. Its compute power is exceeding the requirements by far, battery capacity lasts for one day of activity (or need to be extended by a power bank). Regarding supported technologies, smartphones already bring along many communication and localization technologies, but are limited in terms of extendability towards new technologies by end users.

A dedicated microcontroller-based device creates extra cost ranging from single-digit to up to ca. 100 EUR. It can be integrated into a portable device, but would have to be carried in addition to other electronic devices. It can, however be integrated into a bike or eBike by the manufacturer. The platform can be tailored to provide the necessary compute power and battery capacity, but even Arduino-based devices should suffice. All required communication and localization technologies can be added as needed by a vast amount of available extension boards.

For the hiker, we argue that only smartphone-/smartwatch-based platforms can be considered, as hikers will not be willing to carry an additional device (as also our user study confirmed). For the biker, a dedicated micro-controller platform integrated with the bike is a viable solution, but a smartphone can also be attached and used for the same purpose.

For these reasons and in order to not have to support two different platforms, we opted for a smartphone-based solution for both hiker and biker for our prototype.

B. Communication Technology

Requirements for the communication technology include:

1) *Infrastructure- and setup-less operation*: Communication must be possible without requiring infrastructure or setup procedures between sender and receiver; 2) *Support of periodic one-way broadcast*: Information exchange follows a 'periodic one-way broadcast' pattern, like common in Vehicle-to-X (V2X) messaging like Cooperative Awareness Messages (CAMs) or Basic Safety Messages (BSMs). ETSI Vehicle Awareness Messages (VAMs) can be considered as suitable messaging format; 3) *Range*: Assuming a maximum relative speed of biker and hiker of 30 km/h and six second warning advance requires a minimum communication distance of 50 m. In order to also consider processing delays and occasional cases of higher relative speeds, a communication distance of at least 100 m is desirable; 4) *Data rate and latency*: Messages should be sent at most every 500 ms. A higher sending rate is not necessary for the application and also often not achievable, in particular as many consumer Global Navigation Satellite System (GNSS) devices like Android smartphones typically provide position updates with 1 Hz. According to [10], the average VAM message size is 214 B which leads to a required data rate of 428 B/s. Regarding latency, we assume that any transmission latency

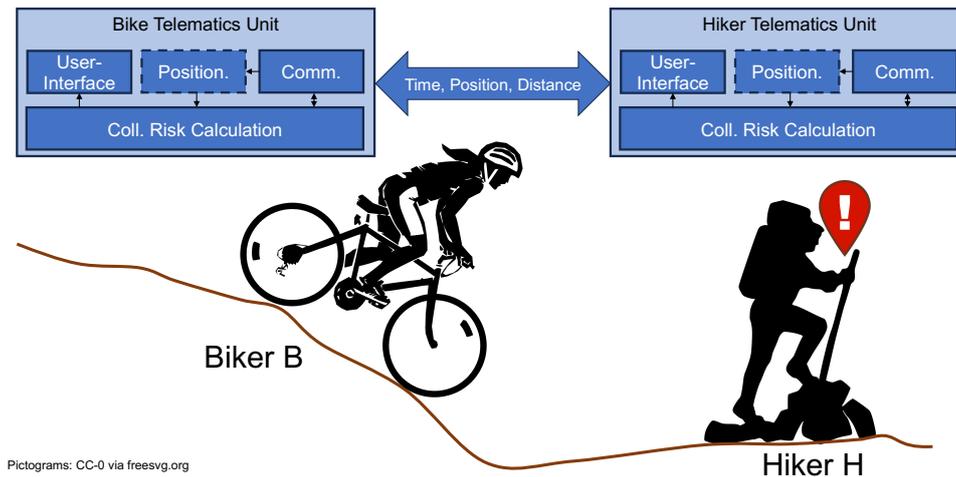


Figure 1: Visualization of Use-Case and System Architecture.

below 100 ms will be acceptable by our system; 5) *Resilient communication*: it is important that the communication system operates reliably in alpine outdoor environments considering vegetation and steep slopes; 6) *Availability in target platform*: the chosen technology must be available for the target platform (or the target platform needs to be changed to support the communication technology).

In our requirements analysis, we consider on the one hand different Wi-Fi-based alternatives and on the other Bluetooth Low Energy (BLE) as those are the ones that initially seem to best fit all of our requirements.

The 801.11 standard provides operation modes (iBSS, Wi-Fi Direct, DSRC/IEEE 802.11p in OCB mode) that can operate infrastructure-less operation and support the requirements set up for one-way broadcast, required range, data rate and latency. Regarding resilient communication, there is only limited analysis on how both systems perform in the considered outdoor environment. Mukhopadhyay and Thakur [11] find that vegetation considerably attenuates 802.11b (Wi-Fi) signals. Similarly, Torshizi et al. [12] tested effects of vegetation on the performance of 802.11n (Wi-Fi) at 5 GHz in terms of data rate and Received Signal Strength Indicator (RSSI). Both parameters showed a significant decrease when trees were positioned between two communication devices.

Both Mathew et al. [13] and Park et al. [14] identify that BLE performance degrades in non line of sight (NLOS) and in the presence of vegetation. They investigate distances between 120 and 20 m with no vegetation, moderate vegetation, and abundant vegetation, respectively and find that the packet loss rate decreased by 20% in the NLOS scenario compared to the line of sight (LOS) scenario. As both technologies have evolved substantially since those studies, a more detailed study how both technologies compare in alpine and outdoor environments would be required to transfer these results.

However, considering the target platform of smartphones, there is a problem with availability of certain communication modes as the two major operating system platforms Android and iOS do not support apps to use iBSS, Wi-Fi Direct is

only usable after a dedicated setup procedure between sender and receiver, and DSRC/IEEE 802.11p are not supported at all.

We therefore consider only BLE which also fulfills all requirements related to infrastructure-less operation, one-way broadcast, required range, data rate and latency, but also can be operated in setup free mode when using extended advertising mode. Note that we are discussing here version 5 of BLE, as at the time of building our prototype, no smartphones or other devices with BLE were available to us. We briefly discuss BLE version 6 changes in the outlook section.

C. Distance Estimation (and Positioning)

The logic needed to implement the MBHWS is relatively simple: one needs to determine if a biker is approaching a hiker and approximate an estimated time-of-arrival (ETOA) when the biker will overtake the hiker. Based on this, an appropriate warning can be issued to the hiker (and possibly also to the biker).

Requirements for distance estimation include: 1) *Precision*: we assume that our warnings can discern distances in 10 m steps. Distance measurements should therefore provide an accuracy of about half of that distance, i.e., 5 m; 2) *Update rate and delay*: as with communication periodicity, an update rate of 1 Hz is considered sufficient, as faster updates can likely not be processed by the user anyways.

We investigated two classes of solutions, the easier one being a simple *distance-based approach*, where we periodically determine the distance between biker and hiker and calculate the ETOA. Distances can be derived either using a ranging technology like the new Channel Sounding feature of BLE v6 or by measuring and exchanging positions (using, for example, GNSS) and calculating the distance.

Alternatively, one could also use additional information like positions on a map with possible tracks that hiker and biker can take to come up with a better ETOA or also rule out a risk of collision if hiker and biker are on physically separated tracks.

For our initial prototype and evaluation, we decided to rely on a simple distance-based approach with positions of hiker and biker being periodically measured by GNSS, exchanged via messaging, and finally distances being calculated using the Haversine equation [15]:

$$d = 2r \arcsin \sqrt{\sin^2 \left(\frac{\theta_2 - \theta_1}{2} \right) + \frac{\cos(\theta_1) \cos(\theta_2) \sin^2 \left(\frac{\lambda_2 - \lambda_1}{2} \right)}{2}} \quad (1)$$

θ and λ represent the latitude and longitude and r the radius of the chosen sphere.

The precision that can be reached depends on the one hand on position accuracy of the GNSS and on the other on communication latency as calculations based on outdated information will provide incorrect ETOA. Note that we neglect altitude differences, as even on alpine slopes they are typically less than 25 % of horizontal distance which leads only to a slight underestimation of the real distance and thus slightly earlier warning, something we consider acceptable.

Achievable update rates and delays depend on the GNSS and properties of the communication system. Whether our approach can fulfill the precision, update rate, and delay requirements is part of our technical evaluation in Section IV.

D. User Interface

For the user interface that conveys the warnings to the hiker (and possibly also to the biker), we consider the following requirements: 1) *Unobtrusive*: the system and its User Interface (UI) should not be overly complicated or require active attention of the hiker (and biker) but rather let them focus on their main task; 2) *Suitable warning modality*: Warnings should be delivered by a modality which cannot be easily missed, and allow to express a severity level based on the ETOA; 3) *Personalization*: As the consideration of what is an unobtrusive or suitable warning may be something depending also on personal taste, the warning mode should be individually configurable.

In our MBHWS, we consider to deliver the warning either via smartphone or via a connected smartwatch. Both are able to deliver visual, acoustic, or haptic warnings.

As visual warnings on a smart-phone or -watch display require active attention of the user, we disregard the visual warning as not fulfilling the unobtrusive requirement and only implement acoustic and haptic warnings. Both should be able to fulfill the unobtrusive requirement and allow to encode the ETOA, for example as frequency of sound or vibration. How people react to these two modalities will be evaluated as part of our user study in Section V.

III. SYSTEM DESIGN AND PROTOTYPE DEVELOPMENT

Based on the requirements analysis from the Section II, we implemented different prototypes of our MBHWS as Android apps written in Kotlin that would run on smartphones both mounted to bikes and carried by hikers.

For localization, we relied exclusively on the Fused Location Provider API provided by Android which would normally resort to GNSS and Wi-Fi for localization, but as Wi-Fi was switched off during our experiments, the initial localization data is only provided by GNSS. For retrieving positions from Android, we used `PRIORITY_HIGH_ACCURACY`, an update interval of 0.1 s, and `ACCESS_FINE_LOCATION`.

For communication, we used a BLE-service that periodically broadcasts the biker's UUID, position as longitude, latitude, and altitude and speed in m/s.

The advertisement interval is set to the lowest possible value of 100 ms which is telling the system to send advertisements as fast as possible. The next chapter evaluates how fast beacons were actually sent. Using advertisement mode, true ad-hoc communication can be established and no device pairing is required. Using Bluetooth 5, we use Low Energy Coded PHY and extended advertisement to achieve a large range and be able to send larger amounts of data.

On the receiving side, the smartphone will use the position of the remote device and of the own device to calculate a distance estimate using the Haversine formula. The estimated time-of-arrival (ETOA) is then calculated as $\frac{\text{determined_distance}}{\text{mtb_speed}}$. The app categorizes the ETOA into three zones:

- $ETOA \leq 3$ s: Near-Zone
- $3 < ETOA \leq 9$ s: Middle-Zone
- $ETOA > 9$ s: Far-Zone

The hiker's app generates different and configurable warnings, depending on which zone an approaching bike is in.

While suitable for our technical evaluation in the next chapter, the prototype still faces potential limitations. For example, we configured it in a very aggressive mode retrieving location estimates as quickly as possible and sending them out as advertisements in high rate. While one would expect battery to drain quickly under these circumstances, we could operate the smartphones during test sessions of 4 – 5 hours without need to recharge. For production use, power consumption should still be optimized.

While our initial prototype had to run as a foreground process, the most recent prototype allows operation as a background process and has a more advanced user interface as shown in Fig. 2. On the left side, it shows an approaching bike at a distance of 6m, approaching at 0.5 m/s. On the right hand side, the Figure shows various configuration options which we added as our pilot user study indicated highly individual preferences regarding warning settings. This led us to the conclusion that the MBHWS should support a broad variety of warning modes that users can configure. One should also note that the warning screen serves mostly for debugging purposes and is not expected to be the main warning modality, but that users would rather rely on acoustic and vibration alarms where the applications runs in the background.

IV. TECHNICAL EVALUATION

Using the prototype described in Section III, we ran technical evaluations using two smartphones, one Samsung

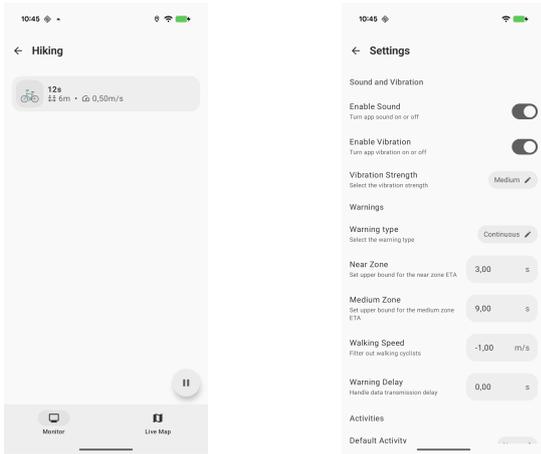


Figure 2: Screenshots of the MBHWS smartphone app. Left: Main screen showing an approaching biker. Right: Settings screen with configuration options.

Galaxy S23+ on the hiker's side and a Samsung Galaxy A70 mounted to the handlebar of a bike. We conducted technical field tests in various locations in around Ulm in Southern Germany and also in Grödnertal/Val Gardena in the Italian Alps to reflect a broad range of different and realistic environments where bikers and hikers meet. Fig. 3 (left) shows one of the test sites on a shared hiking & biking trail, on the right a small road in an open area in Southern Germany.



Figure 3: Coniferous forest



Figure 4: Open field

Goal of our technical evaluation is to gain an understanding how our application performs with respect to GPS update frequency, inter-packet delays and packet loss, precision of distance calculation and maximum possible communication range and whether it fulfills the requirements defined above.

Regarding GPS update frequency, we measured the rate by which the S23+'s FusedLocationProvider provides updates to the application. In the wooded area an average update frequency of 0.911s was measured with a maximum of 1.017s. In open field, the average update frequency was 0.967s with a maximum interval of 1.009s. Essentially, these differences are not significant and fulfill the requirement to receive a position update at 1 Hz. However, we are not able

to determine via the API how old the measurement is when being submitted to the application. So in worst case, this introduces a delay of 1s to our position updates.

With respect to accuracy of calculated distance, we first took measurements using a setup where bike and hiker were statically placed at a known distance (measured through a measurement tape as visible in Fig. 3).

From our measurements shown in Fig. 5, one can observe that average distance measurement errors tend to be stable around 2m in our alpine test site with coniferous forest from Fig. 3. Accuracy also does not seem to be largely affected by distance, even though we measure a little higher standard deviation at single positions.

On the other hand, measurements in a mixed forest test site show a much larger fluctuation and inaccuracies reaching 7m and more. This indicates that in particular broadleaf trees pose a challenge for localization.

Nevertheless, we expect our application to provide useful warnings even at that accuracy as long as communication is possible in time. As we will point out in the future work section, we are also investigating alternative means to provide more accurate distance estimates.

The errors seen can be attributed to multiple facts, including an inherent error of 0.5% introduced by the Haversine equation [16] plus additional errors that stem from inaccuracies in the GNSS positioning.

However, relying on the location provider of Android, it is not possible to identify individual contributions. In other investigation where we used a GNSS device directly [17], we found that positioning in alpine and outdoor environments performs particularly bad in stationary settings like the one we measured and we expect that positioning accuracy would rather enhance once bike and hiker are moving.

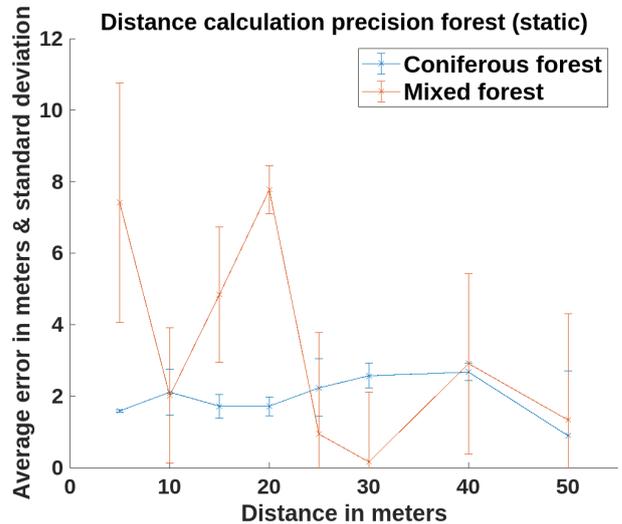


Figure 5: Distance calculation precision with static positions.

We also investigated the performance of communication through BLE advertisements with our prototype. As discussed in Section II-B, we require communication to be possible at least within a range of 50m to allow a warning time of 6s at a relative speed difference of 30 km/h.

These requirements were reliably met and exceeded in our experiments. In the coniferous forest (setting shown in Fig. 3) first advertisements could be received at distances of 150 m and stabilized quickly as distances became shorter. Communication was highly reliable at 50 m. We also conducted measurements on a skiing slope with free line-of-sight between bike and hiker smartphone and here communication was possible independent of forest or open field, starting at 200 m. In the range of 0 to 50 m, average inter-packet delay between two received advertisements was stable at below 0.25 s even without direct line-of-sight and maximum inter-packet delay never exceeded 2 s.

In conclusion, our preliminary technical evaluation showed that localization accuracy provides good results in open fields and coniferous forests in flat and alpine environments, but broadleaf trees degrade localization quality substantially. For the latter case, enhancements to localization should be investigated. Regarding communication, BLE advertisements fulfill our requirements and provide highly stable communication at 50 m range and beyond. While we intend to conduct more detailed evaluations as discussed in Section VI, we can already conclude that our technical setup allows implementation of a MBHWS. This provided the basis to investigate how users perceive our system and we, thus, conducted a user study that we discuss in the next section.

V. USER STUDY

The goal of our hiker study was to investigate how hikers (at which the benefit is particularly targeted) would perceive and accept our MBHWS, but also investigate which modalities for warnings might be preferred by different populations.

A. Participants

In this study, we focused on the hikers and did not investigate the biker’s perspective yet. The study participants therefore represent hikers receiving the one-sided warning. Since hiking is a popular sport at all ages, it is important to include different age groups and especially to consider people of advanced age in order to find out their perception and acceptance of a MBHWS. We recruited twenty-two people to participate in our study. They ranged in age from 19 to 78 with an average of 48.45 years and a standard deviation of 23.38 years. We split the participants in three age groups ranging from 19–40 years, 41–60 years, and 61–78 years. Thus, 40.91% are in the young, 18.18% in the middle and 40.91% in the older group.

B. Study Design

The study aimed to evaluate people’s behaviors relevant to the use of a MBHWS and the effectiveness of the smartphone-based prototype. As a first step, participants had to fill in a questionnaire about their behavior and experiences related to hiking and mountain biking as well as general questions about their use of smartphone and related technologies. The second part consisted of an evaluation of the prototype, in which the participants were acting as the hiker in our scenario and had a bike approaching from behind. Afterwards, they

were interviewed with structured questions and ratings on the perceived effectiveness of the different warnings during the experiment. The full questionnaire is presented in Appendix A. Questions 1–5 were asked before carrying out the experiment, 6–10 after each warning round, and 11–14 after completing all of them. Warning modalities vibration and sound were tested. For both variants, we tested both a continuous warning, becoming stronger in frequency the closer the person gets, and single warnings, which emit single warning signals at pre-defined distances (see Section III).

As we did not include a smartwatch in our prototype implementation, we relied only on smartphones for the testing. As shown in Fig. 6, the smartphone was mounted in an arm sleeve as shown in Fig. 6, the smartphone was mounted in an arm sleeve at a well-defined position to enhance comparability.



Figure 6: Arm sleeve



Figure 7: MTB start position point of view

To simplify and speed up conduction of the study, it was carried out on an even asphalt road as shown in Fig. 7. While it may be argued that this is not the typical environment for our application, also outdoor environments have different surfaces (including asphalt) and inclinations. As future work, studies in more varying environments are planned. Fig. 7 shows the point of view from the mountain biker’s starting position with the hiker starting at the rear end of the image at a distance of 100 meters.

For each participant, there were a total of five warning rounds. In each round, the hiker was given instructions to walk at steady pace in one direction away from the approaching biker and not to turn or look back but rely only on the warnings given by the smartphone. The second person (not being part of the study participants) acting as the biker then started to approach the participant at a constant speed of 17–20 km/s starting from distance of 100 m. The biker eventually passed the participant in close distance of approx. 50 cm.

This procedure was carried out in total five times. Round 0 served as a reference round with no warnings, round 1 used continuous vibration (“con vib”), round 2 single vibrations (“sin vib”), round 3 continuous sound (“con sou”) and round 4 single sounds (“sin sou”) as warning modality.

C. Results

In the evaluation of the reference round, which was carried out without using a MBHWS, 4.5 % of participants replied in the subsequent interview that they were scared by the cyclist. 59.1 % stated that they noticed the cyclist, but too late, so they would not have had enough time to react appropriately (like moving to the side). 18.2 % answered they had just enough

time to react and another 18.2 % felt that they had more than enough time. So generalizing over all age groups, a majority of 63.6 % stated that they did not have the opportunity to react to the approaching cyclist appropriately. In the individual age groups, these percentages were 55.55 % of young people and 66.66 % of older people. This suggests that with increasing age, the ability to perceive the outside world becomes weaker and therefore cyclists are recognized later.

	Not warned	Bad	Good	Very Good
contin. vibration	9.09%	13.64%	40.91%	36.36%
single vibrations	9.09%	50%	36.36%	4.55%
continuous sound	0%	0%	22.73%	77.27%
single sounds	0%	27.27%	40.91%	31.82%

Table I: Survey results for effectiveness evaluation of warning variants

con vib	sin vib	con sou	sin sou
45.45%	4.55%	60.01%	31.82 %

Table II: Survey results for warning variants for personal usage

	con vib	sin vib	con sou	sin sou
Young group	77.78%	0%	44.44%	33.33%
Older group	11.11%	11.11%	88.89%	22.22%

Table III: Survey results for warning variants for personal usage separated on age

The results shown in Table I were then obtained in the subsequent four rounds of our experiments. The participants were requested to rate the effectiveness of the warnings according to the ratings shown in the table. Here, “Not warned” means that the respective participant did not perceive the warning signals at all while bad to very good provide an subjective indication how well the signal was perceivable. As one can see from the results, the rounds in which vibrations were used were generally rated worse than those with sounds. In the rounds with vibrations, some participants (all belonging to the older age group) did not perceive the warnings at all. It can be concluded that acoustic warning signals are easier perceivable and thus more effective as a warning than vibrations. Furthermore, there is also a clearly notable difference between continuous and single warnings where continuous warnings are rated substantially better for both acoustic and haptic warnings compared to single warnings.

In order to assess not only the effectiveness, but also personal preferences, participants were also asked which modality they prefer to use when hiking. This also takes into account, e.g., whether they considered an acoustic warning to be too annoying for their environment. They could, however, also express preference for combinations of warning methods. As shown in Table II, continuous variants are preferred for personal use and acoustic warnings beat vibrations.

Splitting into the different age groups (shown in Table III), continuous sound is preferred by older and continuous vibration to a similar extent by younger group people. This also confirms that continuous signals are preferred in general.

As such preferences are also very dependent on the individual, an MBHWS should offer the user the possibility to choose the preferred warning modality.

Next, participants were asked how much time they had to react to the warning using their preferred warning method as a reference. Here, 4.5 % stated they did not have enough time to react to the warning. 68.2 % stated that they had enough time and 27.3 % that they had more than enough time to respond to the warnings. So for 95.5 % of participants, the MBHWS allowed them to react in time to an approaching mounter biker, compared to only 36,4 % without MBHWS. An improvement in the hiker’s perception of the mountain bikers with the help of a MBHWS is thus clearly recognizable.

Finally, in order to assess user acceptance, the participants were asked whether they would use a smartphone-based MBHWS like the one in the study on a private hike or even buy an external device. 95.5 % stated that they would use a smartphone-based MBHWS and 27.3 % would even be willing to purchase a dedicated external device that is not related to a smartphone in order to use the functionality of a MBHWS. Thus, a MBHWS seems a highly attractive application were high user acceptance and adoption can be expected.

VI. CONCLUSION AND FUTURE WORK

In this paper, we introduce a novel application idea for V2X communication and Vulnerable Road User (VRU) protection, namely a Mountain-Bike-to-Hiker Warning System (MBHWS). We assess use-cases, scenarios, and requirements for implementing a MBHWS and identified smartphones, GNSS, and BLE advertisements as suitable base technologies on which we implemented fully functional prototypes.

A user study with 22 participants revealed first insights into user acceptance and preferences. According to our results, a MBHWS would enable substantially more people to react to overtaking mountain bikes with sufficient time to avoid critical situations or simply to not be scared (95.5 % with vs. 36,4 % without MBHWS and user acceptance and adoption would be very high.

However, our analysis has also limitations and we envision a number of next steps for future work. Novel technologies, which were not yet introduced into smartphones or otherwise available at the time of our experiments provide explicit support for determining the distance between two devices. Namely, Bluetooth version 6 introduces a channel sounding feature and such technology will also become part of future IEEE 802.11 bd devices. We aim to also evaluate these technology for their performance in our setting and particular focus should be put on certain types of forests were GNSS suffered from inaccuracies. Furthermore, IEEE 802.11 p/bd should be investigated as an alternative to BLE for communication, even if BLE has proven to be highly effective for our use-case. However, deployment in smartphones is unlikely anyways.

Next, we aim to investigate more refined warning strategies that provide a better ETOA estimate. For example, one could leverage on map knowledge to assess a more exact distance the bike would have to travel before reaching the hiker. Regarding the user-interface, more modalities and ways to signal the

ETOA to hikers should be explored, as well as warnings that are issued to the biker as well. With all these in place, larger user studies are advisable to base our conclusions on more large-scale results. We also require more testing on truly rocky terrain, requiring more sturdy prototypes, but also additional safety precautions during testing. Ultimately, commercial potential of a MBHWS should be explored together with industry to bring its benefits to actual users quickly.

REFERENCES

- [1] PR Newswire. "Mountain Bike Market size is set to grow by USD 3.77 billion from 2024-2028, Mountain biking tourism acts as catalyst for economic development to boost the market growth, Technavio." (2024), [Online]. Available: <https://finance.yahoo.com/news/mountain-bike-market-size-set-142400390.html> (visited on 2024-09-26).
- [2] S. Palwe. "Mountain Bike Market Research Report Information By Product (E-Mountain Bikes and Standard Mountain Bikes), By Type (Cross Country Bikes, All Mountain Bikes, Downhill Bikes, Freeride Bikes and Dirt Jumping Bikes), By Application (Racing and Leisure), And By Region (North America, Europe, Asia-Pacific, And Rest Of The World) - Market Forecast Till 2030." (2024), [Online]. Available: <https://www.marketresearchfuture.com/reports/mountain-bike-market-5165> (visited on 2024-09-26).
- [3] P. Zajc and N. Berzelak, "Riding styles and characteristics of rides among Slovenian mountain bikers and management challenges," *Journal of Outdoor Recreation and Tourism (JORT)*, vol. 15, pp. 10–19, Oct. 2016.
- [4] C. M. Pickering and S. Rossi, "Mountain biking in peri-urban parks: Social factors influencing perceptions of conflicts in three popular National Parks in Australia," *Journal of Outdoor Recreation and Tourism*, vol. 15, pp. 71–81, 2016, Mountain biking: Challenges and benefits. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S221307801630038X>.
- [5] S. Tourism. "Information on mountain biking." (2025), [Online]. Available: <https://www.myswitzerland.com/en/experiences/summer-autumn/bicycle-mountain-bike/mountain-biking/information-on-mountain-biking> (visited on 2025-02-13).
- [6] E. M. Foundation. "Hiker injured in crash with cyclist on trail near Danville." (2015), [Online]. Available: <https://www.danvillesanramon.com/news/2015/06/17/hiker-injured-in-crash-with-cyclist-on-trail-near-danville/> (visited on 2025-02-13).
- [7] S. McManis. "Mountain bikers, hikers, horse riders on collision course." (2010), [Online]. Available: <https://www.mercedesunstar.com/sports/outdoors/article3247498.html> (visited on 2025-02-13).
- [8] "Swisstrailbell." (2025), [Online]. Available: <https://trailbell.de/> (visited on 2025-02-13).
- [9] M. Hörmann, M. Marx, M. Segata, M. Zucchelli, and F. Kargl, "Poster: MBHWS — a Mountainbike-to-Hiker Warning System," in *2025 IEEE Vehicular Networking Conference (VNC)*, 2025, pp. 1–2.
- [10] S. Lobo, A. Festag, and C. Facchi, "Enhancing the Safety of Vulnerable Road Users: Messaging Protocols for V2X Communication," in *2022 IEEE 96th Vehicular Technology Conference (VTC2022-Fall)*, 2022, pp. 1–7.
- [11] A. Mukhopadhyay and J. P. S. Thakur, "Study of Fading at 2.4 GHz WLAN in Tree and Foliage Environment," in *2018 International Conference on Recent Innovations in Electrical, Electronics & Communication Engineering (ICRIEECE)*, IEEE, 2018, pp. 1377–1380.
- [12] S. D. S. Torshizi, K. K. Lo, K. H. Kwong, A. T. K. Ngoh, M. Abbas, F. Hashim, and H. S. Lim, "An investigation of vegetation effect on the performance of IEEE 802.11 n technology at 5.18 GHz," -, 2012.
- [13] K. Mathew and M. Tabassum, "Analysis of bluetooth and zigbee signal penetration and interference in foliage," in *the proceedings of the International MultiConference of Engineers and Computer Scientists*, vol. 2, 2016, pp. 16–18.
- [14] H. Park, S. Lee, E. Moon, S. H. Ahmed, and D. Kim, "Performance analysis of bicycle-to-pedestrian safety application using bluetooth low energy," in *Proceedings of the International Conference on Research in Adaptive and Convergent Systems*, 2017, pp. 160–165.
- [15] H. Mahmoud and N. Akkari, "Shortest Path Calculation: A Comparative Study for Location-Based Recommender System," in *2016 World Symposium on Computer Applications & Research (WSCAR)*, 2016, pp. 1–5.

- [16] A. Andreou, C. X. Mavromoustakis, J. M. Batalla, E. K. Markakis, G. Mastorakis, and S. Mumtaz, "UAV Trajectory Optimisation in Smart Cities Using Modified A* Algorithm Combined With Haversine and Vincenty Formulas," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 8, pp. 9757–9769, 2023.
- [17] M. Zucchelli, M. Marx, M. L. Hörmann, F. Kargl, and M. Segata, "Challenges and Initial Measurements on Communication and Localization for Mountain Bike Safety Applications," in *20th IEEE/IFIP Wireless On-demand Network systems and Services Conference (WONS 2025)*, Hintertux, Austria: IEEE, Jan. 2025.

APPENDIX

A. Questionnaire

Bicycle-to-smartphone communication for a hiker early warning system
User survey

General questions

1. How old are you?
2. How often do you carry out the following activities?

Hiking				
●	●	●	●	●
never	rarely	often	regularly	
Mountain biking				
●	●	●	●	●
never	rarely	often	regularly	
3. Which statement applies to you with regard to the conflict between hikers and mountain bikers? Tick one statement.
 - I heard about the conflict for the first time in the course of this thesis
 - I have already heard about the conflict, but have not experienced it personally
 - I myself have already experienced this conflict
4. How do you carry your mobile phone with you in everyday life? Tick the answer that is most likely to apply.
 - I do not carry it with me
 - Trousers pocket
 - Handbag/backpack/bum bag
 - Arm sleeve/arm mobile phone cover
 - Wearable phone cases
5. Do you wear a smartwatch in everyday life?
 - Yes
 - No

Application-related questions

6. Did you notice the mountain biker without warnings (round 0) in enough time to react accordingly? Tick one statement.
 - No, the mountain biker scared me
 - No, I did notice the mountain biker, but there wouldn't have been enough time to react
 - Yes, I noticed the mountain biker, but it was just enough time for a reaction
 - Yes, I noticed the mountain biker and had more than enough time to react.
7. How well did you feel warned of the mountain biker by a **continuous vibration** (round 1)?

●	●	●	●
Not warned	Bad	Good	Very good
8. How well did you feel warned of the mountain biker by **non-continuous (single) vibrations** (round 2)?

●	●	●	●
Not warned	Bad	Good	Very good
9. How well did you feel warned of the mountain biker by a **continuous sound** (round 3)?

●	●	●	●
Not warned	Bad	Good	Very good
10. How well did you feel warned of the mountain biker by **non-continuous (single) sounds** (round 4)?

●	●	●	●
Not warned	Bad	Good	Very good
11. Which variant of the warning signals listed above would you (most likely) want to use on a private hike? Multiple answers are possible.
 - continuous vibration (round 1)
 - non-continuous (single) vibrations (round 2)
 - continuous sound (round 3)
 - non-continuous (single) sounds (round 4)
12. How did you feel about the time you had to react to the warning?

●	●	●	●
not enough	barely enough	enough	more than enough
13. Would you be willing to use a warning system for hikers that runs on your smartphone?
 - Yes
 - No
14. Would you be willing to use an external device (other than your smartphone) for the warning system for hikers? Be aware that there would be a corresponding purchase cost.
 - Yes
 - No