Impact of Radio Range on Contact Characteristics in Bus-based Delay Tolerant Networks

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***Abstract*—In bus-based delay tolerant networks the duration of a contact between two nodes limits the amount of data that can be transferred. For the implementation of such networks it is important to determine which contact durations can be expected. Moreover, this information can be used by scheduling and routing algorithms to increase efficiency. In this paper we structure and characterize the different types of contacts and examine the effects of radio range on contact duration. For realistic results we experimentally investigate the typical range of IEEE 802.11a/b and use a real mobility trace of a large-scale public transport network. We report the simulation results for different types of contacts and the probability distribution of contact durations for various realistic ranges. Furthermore we show that the angle of contacts is an appropriate criterion for the classification of contacts, and propose to use it as input for routing and scheduling decisions.**

I. Introduction

Public transportation busses are perfect examples of well suited data mules for delay tolerant networks [1] (DTNs). These vehicles cover a large area of operation, move almost always on predetermined routes and frequently encounter other vehicles. Therefore, bus-based DTNs can serve as high capacity and relatively low latency backbones. Several architectures, applications and routing schemes for bus-based DTNs have been proposed, e.g. in [2]–[7]. Prior work on mobility properties [8] and mobility modeling [9] of bus-based DTNs focuses on inter-contact time. In this paper we analyze another important metric - the duration of contacts. Contact duration has a direct impact on the amount of data that can be transferred during one encounter. In [10] this amount has been experimentally evaluated for a vehicle which drives past a WLAN access point on a highway. However, these results cannot be applied to bus-based DTNs, in which a wireless connection is established when two vehicles get within each others radio range. The connection then remains available until the distance between the moving vehicles exceeds the radio range. Distance, range and vehicle speed are the main impact factors on contact duration, as we investigated in [6]. Distance and speed are dictated by road and traffic conditions, these variables are complex and hard to influence during system design. In contrast, range can be influenced by choosing the wireless technology, hardware (e.g. radio, antenna) and software (e.g. transmit power control algorithms implemented in firmware or driver).

The goal of this paper is to characterize types of contacts and the effect of range on contact duration, to gain new insights for the system design and for routing algorithms in real-word bus-based DTNs. Moreover, a deeper understanding of contact duration classes is important for the implementation of quality of service (QoS). Our approach to obtain realistic results is to use mobility traces of a real large-scale public transport network.

The remainder of this paper is organized as follows. In Section II we determine which radio ranges are to be expected in a realistic scenario. An overview of four basic types of contacts is given in Section III. Section IV introduces our simulation setup and the underlying mobility trace. Furthermore we present an exemplary analysis of how the basic types of contacts are influenced by variation of range. In Section V we subclassify these contacts based on a theoretical analysis as well as simulation, and present the characteristics of the contact classes. Finally, in Section VI, we sum up the results and propose future work.

II. WLAN Radio Ranges

Bus-based DTNs will likely use the omnipresent IEEE 802.11 technology to communicate between vehicles. IEEE 802.11b/g has been state of the art for home networks in the 2.4 GHz band and now the 5 GHz band is used as well. Especially for vehicular networks, IEEE 802.11p is in development. Unfortunately, so far there are neither off-the-shelf hardware systems nor thorough evaluation studies of such 802.11p systems. Since 802.11a is the closest relative, we use its performance characteristics as basis in this paper. To the best of our knowledge, no measurements of 802.11a in a public transport environment have been published yet. Therefore, we have conducted measurements to determine the necessary parameters for simulations of DTNs.

In 2007 [6] we looked into the characteristics of IEEE 802.11b wireless LAN between two moving cars. In a controlled environment with a direct line of sight between the two cars we were able to achieve ranges well above 500 m. With dynamic rate adaptation the full rate of 11 Mbit/s was achieved below 202 m. We also found out that the relative speed of the vehicles does not have a significant impact on the radio communication. In another measurement in a city environment we found a maximum range of 171 m between the cars whereas more than 90 % of the packets were transferred with a nominal speed of 11 Mbit/s.

To obtain similar information for IEEE 802.11a we have now used the following set up. We placed a static node 3 m above the ground and installed a mobile node on the roof of a vehicle. The nodes have used antennas with a total path gain of 11 dBi. Both stations used a Ubiquiti XR5 [11] IEEE 802.11a WLAN card. In order to measure the bandwidth of the WLAN connection on the application layer, we have used iPerf [12] with TCP.

To test the communication characteristics, the vehicle was placed 350 m away from the station. It starts to drive towards the station, uses a roundabout to turn around in front of the station and then drives away again. The targeted speed is 45 km/h which is a usual speed for inner city vehicles in Europe. The distance of 350 m was chosen since it was the maximum distance over which communication was possible. The measurements were performed at a street in an industry park with trailers and buildings located right next to the street and can therefore be characterized as a semi-controlled environment. The sender and receiver were always in direct line of sight and no other traffic was present.

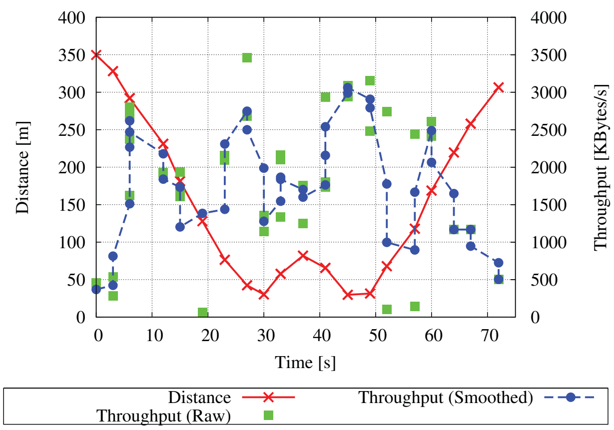


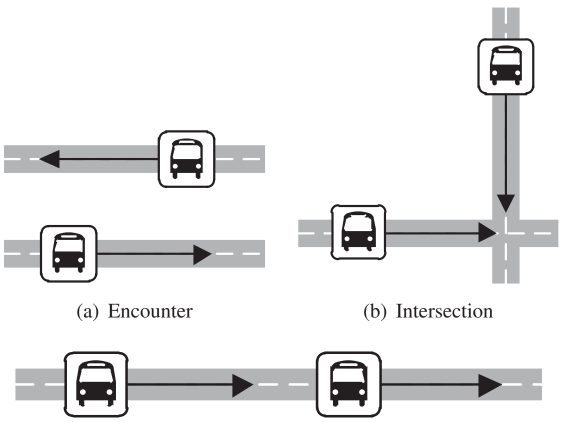
Figure 1. Sender-Receiver distance and achievable application layer throughput over measurement time for one exemplary measurement.

Figure 1 shows the distance between the sender and the receiver. The w-shape is caused by the roundabout next to the static node. In addition, the figure shows the bandwidth that could be achieved on application level in one of the measurements. The fluctuations are due to interference and multi-path propagation caused by surrounding objects. The average bandwidth of all measurements is 1587.88 Kbytes/s.

As we have learned from the measurements in 2007, the transition from results in a controlled environment to the real world reduces the achievable results. For 802.11a, we have used a semi-controlled environment. We therefore assume that the achieved range can also be reached in a real-world network.

III. Basic Contact Types

In a bus-based DTN vehicles move on predetermined routes which result in different contact types between vehicles as shown in Figure 2.



(a) Encounter (b) Intersection

(c) Following

Figure 2. Basic Contact Types

1) *Encounter:* Two vehicles pass each other in opposite directions (see Figure 2(a)).
2) *Intersection:* Two vehicles pass each other in orthogonal directions (see Figure 2(b)).
3) *Following:* One vehicle follows another over a certain path length (see Figure 2(c)).
4) *Not Moving:* One vehicles passes by a vehicle which does not move.

One specialty of public transport networks is that vehicles of the same line usually only have “encounter” and “following” contacts. We refer to the superset of these two sets as “overlapping”. Lines are planned in a way that there is no intersection between vehicles of the same line. However, contacts between different lines can be each of the above types and depend on the predetermined routes and cannot be generalized.

During a contact we refer to the time that two vehicles are within communication range as contact duration. For each of the four types exist a different expected contact time which we discuss in section V.

IV. Simulation with Real Mobility Traces

The movement of vehicles in an urban environment is influenced by many external factors. Traffic lights, other vehicles, rush-hour congestion, breakdowns and construction sites are just a few examples. Because of this high complexity we decided against a synthetic mobility model for the simulations. Instead, we chose a mobility trace of more than 1600 busses in Chicago. Its characteristics, a report of its acquisition and processing, and its position interpolation and accuracy is described in [13]. This trace was used as an external movement file for The ONE [14] simulator. The simulation scenario and the mobility trace are available for download[1].

[1] http://www.ibr.cs.tu-bs.de/bustraces

Although we presented experimentally determined ranges for 802.11a/b in Section II, simulations are performed in 50 m steps from 50 m to 500 m. This is not realistic for current 802.11a hardware, but we simulate these ranges since results can be applied to other wireless technologies and setups as well. For the simulation we chose a simple circular antenna radiation pattern. The influence of structures such as buildings and vehicles are excluded from the simulation. These two assumptions are reasonable since our work focuses on real world mobility in public transportation systems, and not on radio propagation and channel models.

The mobility traces include up to 1600 active vehicles at the same time which mainly move at speeds below 35 km/h. The positions of the buses were recorded using automated vehicle location systems (AVL) installed by the Chicago Transport Authority (CTA). The busses have sent a GPS position update every 20 to 40 seconds and we have used extrapolation as described in [15] to achieve a granularity of one second.

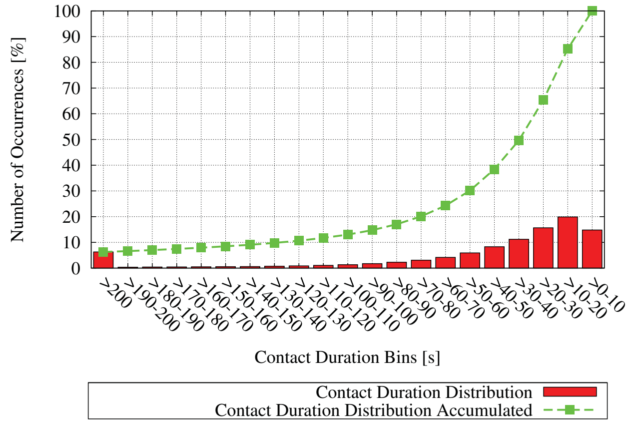


Figure 3. Histogram of vehicle contact durations for a range of 100 m for all busses

For the presentation of simulation results we start with an exemplary range of 100 m and analyze all 161237 connections within the scenario. The bars in figure 3 show the probability distribution of the contact durations. Our statistical analysis results shows that the median is 30 s and 50% of the contacts are between 16 s and 59 s long. The graph above the bars shows the accumulated probabilities, i.e. the probability that a contact will last at least for a given time within the interval. This value is important for predicting the amount of data that can be transferred during a contact.

In figure 4 the accumulated probabilities for all ranges are shown. As expected the average contact durations increase with higher ranges. However, it is notable that there is a steeper rise at low ranges, but generally on a lesser level.

In order to examine if the different types of contacts are affected differently by a variation of range, certain exemplary groups of vehicles were isolated. Figure 5 shows the median connection duration for these groups. First, the median of all vehicles in the scenario is plotted (denominated with “all contacts”). Then vehicles on two exemplary isolated lines are

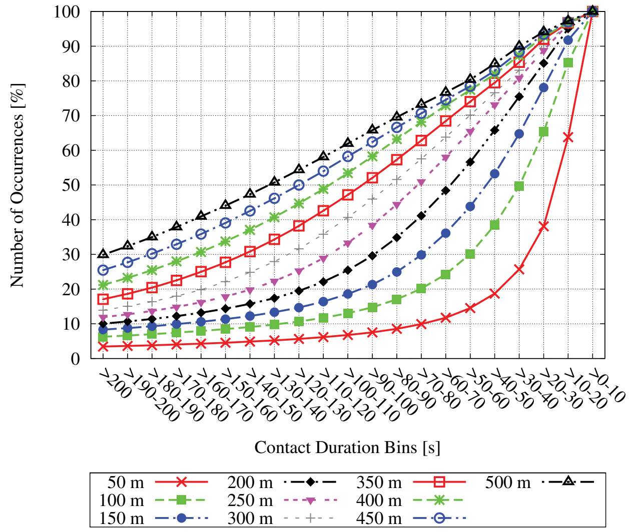


Figure 4. Accumulated probability distribution of vehicle contact duration for a range of 100 m for all busses

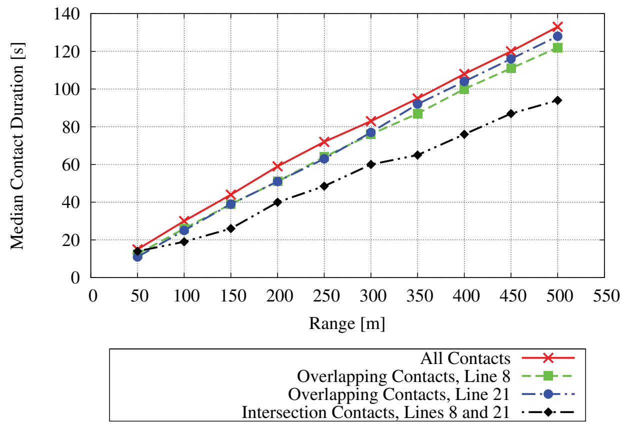


Figure 5. Median contact durations for different ranges for all busses

selected: lines 8 and line 21. This means that only overlapping contacts are in these subsets. There is a slight offset between the medians of these two subsets and the set of all vehicles. This is due to average vehicle speeds on the selected lines, which is slightly different from the average speed of all vehicles. Nevertheless, these two graphs are still very similar to the graph of all vehicles. Starting at 350 m, the graph shows that the median contact duration increases for line 21. This is caused by a higher number of vehicles and subsequently a lower distance between vehicles of that line. This leads to contacts between vehicles following each other in a certain distance.

Figure 6 shows only contacts of vehicles on overlapping segments and figure 7 shows only intersection contacts. Contacts on overlapping segments have a duration median of 87 s with 50% of the samples between 65 s and 126 s while contacts at intersections have a median of 65 s and with 50% of

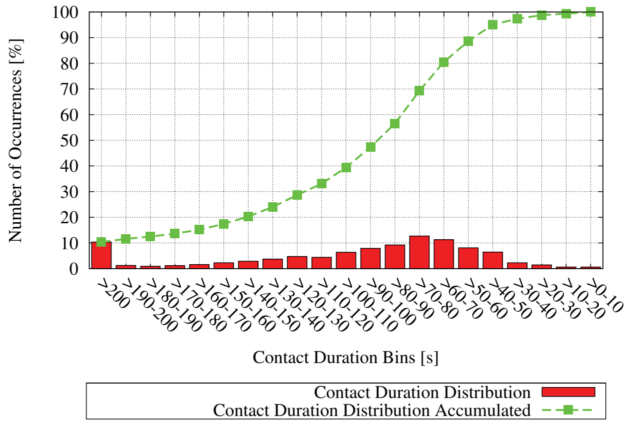


Figure 6. Histogram of vehicle contact durations for a range of 350 m for overlapping contacts

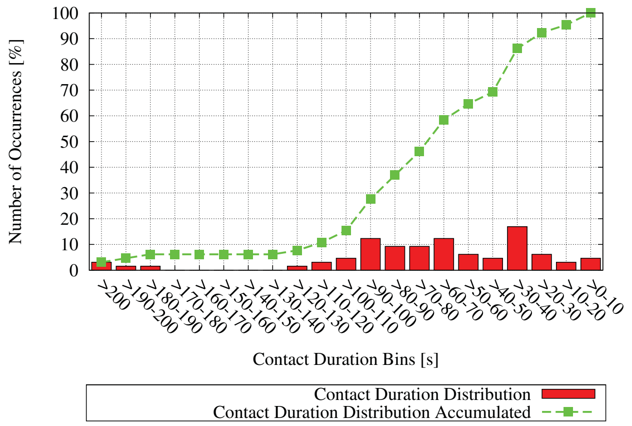


Figure 7. Histogram of vehicle contact durations for a range of 350 m for intersection contacts

the samples between 35 s and 95 s. Note that the distribution of contact durations also looks completely different in the case of intersection contacts. This shows that there is a higher variance because of external events such as traffic lights and traffic conditions.

V. Classification by Contact-Angle

In the previous section two basic types of contacts were isolated based on exemplary lines and routes of the operator's network map. Now we examine if the relative angle at which two vehicles make contact is an appropriate criterion for a more fine grained classification of contacts. Using the angle is advantageous for practical reasons. In a real world public transport scenario the vehicles are usually equipped with GPS-receivers, so that the vehicle orientation is easily available. To calculate the relative angle of a contact the vehicles have to communicate each others orientation at the beginning of a contact. This does not require any additional protocol mechanisms since discovery such as IPND [16] is already implemented and used to exchange information at the beginning of a contact. Routing and scheduling algorithms can exploit the relative angle to assign a contact to a class with certain properties. Therefore it is possible to estimate contact duration based on the statistical properties of a class, resulting in better scheduling and routing decisions. For the analysis we divide all contacts resulting from the simulation with the real mobility trace into five disjoint subsets. These subsets are based on the relative vehicle angle and named after the situation of the contact:

- Encounter: contacts with relative angles of $180° \pm 10°$ which means that vehicles drive in opposite directions. This is the most intuitive contact with two vehicles driving towards each other before making contact.
- Following: all contacts in which the vehicles relative angle is $0° \pm 10°$. This situation corresponds to a contact at an overlapping road segment in which both vehicles drive in roughly the same direction, e.g. when one vehicle follows the other.
- Intersection: Contacts which occur at an angle of $90° \pm 10°$, typically at intersections.
- Not Moving: contacts during which at least one vehicle is not moving. These are usually pausing or inactive vehicles. This means that it is not possible to calculate the angle since there is no movement vector for at least one vehicle. Nevertheless important information on the situation can be derived.
- Ambiguous: This class contains ambiguous contacts that cannot be assigned to a situation because the angle is not close enough to $0°$, $90°$ or $180°$.

The angle is determined by contact vectors, which start at the position of the vehicle at the beginning of the contact and end at the position at which the contact ends. We define the angle as the lesser angle between both contact vectors. Therefore the angle is between $0°$ and $180°$. A tolerance of $\pm 10°$ was allowed so that situations are also recognized with GPS inaccuracies, at slightly curved roads and at changing lanes. Note that the two basic types of contacts in the previous section were based on the selection of vehicles that operate on exemplary lines. Now the selection is determined by the angle and more fine-grained. This also means that the basic contact type at overlapping lines is now subclassified by the vehicles direction, resulting in the classes "Encounter" and "Following"

A. *Theoretical Analysis of Contact Duration*

To gain a better understanding of the different situations in which contacts occur we start with a theoretical analysis of the contact duration. In this analysis, we make a number of simplifying assumptions. Namely, we assume that vehicles maintain a constant speed during the contact. We also assume that no obstacles block the communication of the vehicles and that the range has a circular shape around nodes. In addition, we assume that vehicles do not change the direction relative to each other during a contact.

1) Encounter: In an encounter situation as shown in Figure 8, two vehicles drive towards each other in opposite directions. As soon as the distance between the vehicles is below the range r, wireless communication can happen. After

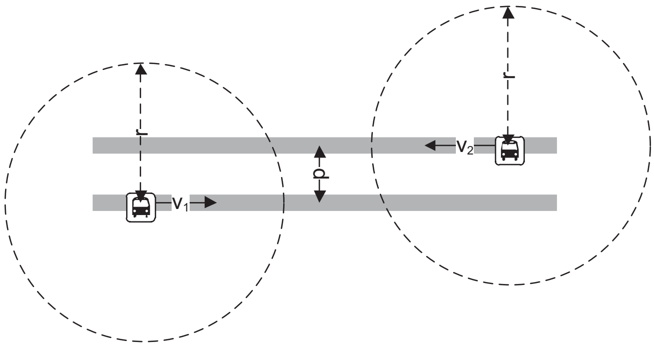


Figure 8. Encounter Contact in which two vehicles drive past each other

passing each other, the vehicles are still able to communicate while they are within range.

$$t_c = \frac{2\sqrt{r^2 - d^2}}{v_1 + v_2} \tag{1}$$

The contact time depends on the speed of the two vehicles v_1 and v_2 as well as the range r and the distance between the vehicles while passing by each other d. Intuitively, this is the distance between the lanes of the road on which the two vehicles make contact. Subsequently, the time can be calculated according to equation 1.

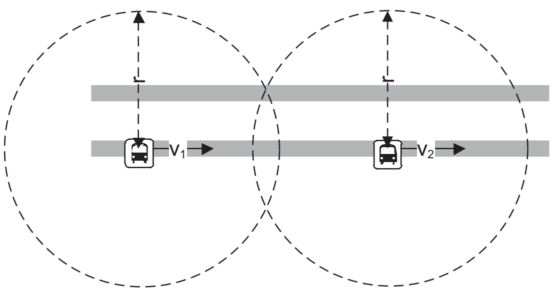


Figure 9. Following Contact in which two vehicles follow each other

2) Following: In a following situation as shown in Figure 9, two vehicles drive in the same direction but have a certain distance between each other. Depending on the relative speed, the two vehicles may overtake or stay behind each other. In practice, this contact type can be found when vehicles of the same line have a distance below the radio range.

$$t_c = \frac{2r}{v_2 - v_1} \tag{2}$$

The contact time depends on the speed of the two vehicles v_1 and v_2 as well as the range r and can be calculated according to equation 2. If the vehicles drive exactly the same speed, the contact should last indefinitely long.

3) Intersection: Another contact type is two vehicles meeting at an intersection as shown in Figure 10. The vehicles can establish communication while approaching the intersection

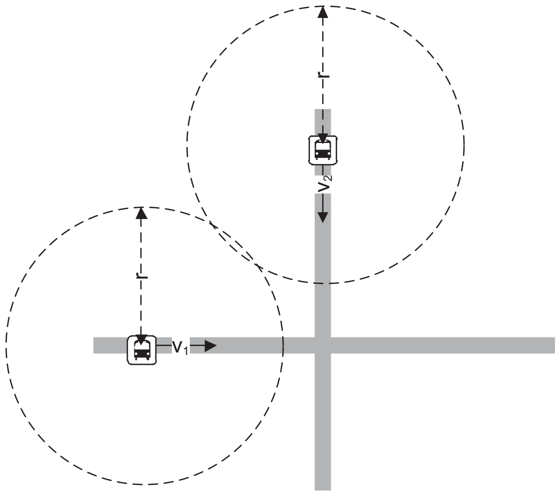


Figure 10. Intersection Contact in which two vehicles meet an an intersection

and stay connected while passing the intersection. The connection eventually breaks down as soon as the vehicles are out of range again. The direction of the two vehicles is orthogonal.

$$t_c = \frac{2\sqrt{2}r}{v_1 + v_2} \tag{3}$$

The contact time depends on the speed of the two vehicles v_1 and v_2 and on the range r. Equation 3 can be used to calculate the contact time under the simplifying assumptions that both vehicles are equally far apart from the intersection at the beginning of the contact.

$$t_{encounter} = \frac{2r}{v_1 + v_2} < t_{intersection} = \frac{2\sqrt{2}r}{v_1 + v_2} \tag{4}$$

Counter-intuitively, it can be seen, that without obstacles blocking communication, contacts of the type intersection are generally longer than contacts of type encounter. This is caused by the fact, that in an encounter the two speeds of the vehicles add up while in an intersection contact, the speeds are independent. Assuming a lane distance of $d = 0$, equation 4 shows the difference. Hence, it can be expected, that intersection contacts are $\sqrt{2}$ times as long as encounter contacts.

4) Not Moving: A situation in which one of two vehicles that are making contact does not move is shown in Figure 11. In this case, no contact angle can be calculated, since the not moving vehicle does not have a driving direction. In practice, this contact type can be found when one vehicle is waiting at a traffic light and the other vehicle is passing by. However, this case is similar to an encounter (see section V-A1) in which the speed of one vehicle is zero. The passing distance d is the minimum distance that the two vehicles have while passing each other.

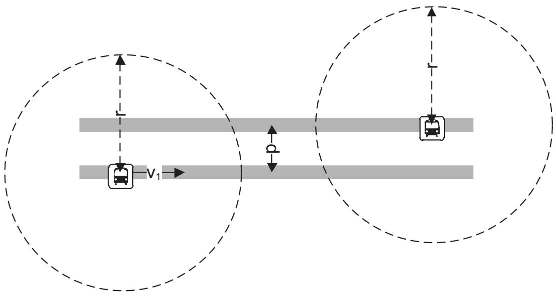


Figure 11. Non Moving Contact in which one vehicle drives past a stationary vehicle

$$t_c = \frac{2\sqrt{r^2 - d^2}}{v} \tag{5}$$

Hence, the contact time depends on the speed of the moving vehicle v and on the range r and can be calculated according to equation 5.

B. *Characteristics of Classes determined by Contact-Angle*

Now all contacts in the trace are classified by contact-angle. Figure 12 shows the amount of contacts in each class. As expected the amount increases at higher ranges. The class "encounter" contains more than twice as many contacts as "following" but shows a similar growth with increasing range. "Intersection" contacts are more effected by increased range. This can be explained by the likeliness of contacts, which is higher for a larger range. Class "ambiguous" shows the highest sensitivity to range, because with higher range, vehicles can drive farther during a contact. This increases the probability that a vehicle changes its direction (e.g. by taking a turn or changing a lane) during the contact. Therefore it is more likely that the angle cannot be assigned unambiguously. For more details on how this can affect the classification, please see Section V.

Nevertheless, the classes still show distinct characteristics, as described in the following.

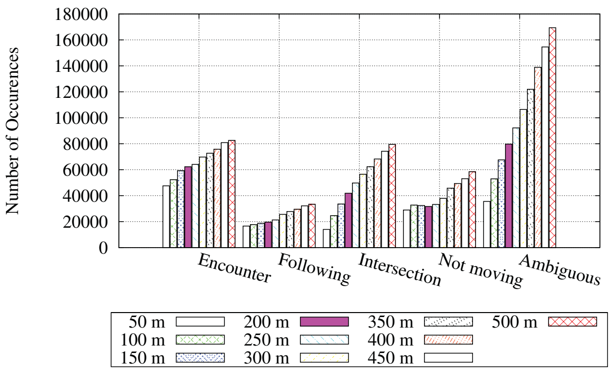


Figure 12. Absolute amount of contacts in the five classes over ranges from 50 m to 500 m (50 m intervals, from left to right)

The median duration of contacts is plotted in figure 13. At low ranges significant differences can be observed. Because of the higher relative vehicle speeds "Encounter" contacts are much shorter than "Following" contacts, which have the lowest relative vehicle speeds. With increasing range the differences between the classes get less distinct, but are still clearly visible even at 500 m.

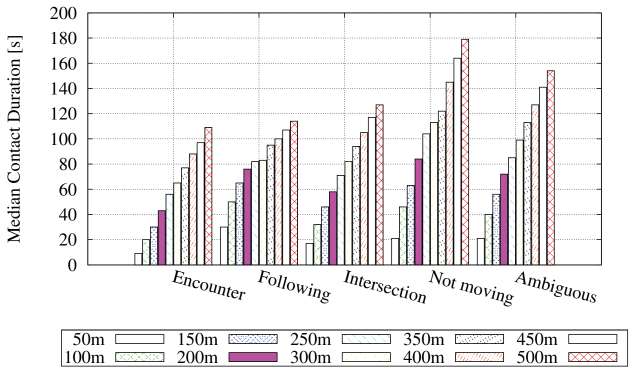


Figure 13. Median duration of contacts in the five classes over ranges from 50 m to 500 m (50 m intervals, from left to right)

A quick glance at the cumulative distribution functions (CDFs) of the contact durations in figures 14 to 18 already reveals that there are special and clearly distinctive characteristics to each contact class. Each CDF "fingerprint" provides precious information to routing and scheduling algorithms, since it enables the prediction of contact duration. The CDF of class "encounter" in figure 14, for example, shows that a contact duration is 50 s or longer for a range of 500 m is very likely. Furthermore the CDFs are very useful for system design and capacity planning, for example when a certain performance is required and the antenna gain has to be dimensioned.

Lets take an exemplary closer look at the CDFs of "encounter" in figure 14 and "not moving" in figure 17. Apparently not moving vehicles are more likely to have significantly longer contact durations. The effect of increased range is also more pronounced and results in a gain of roughly 20 s average duration per 50 m additional range. For the range of 350 m that we measured in section II this means that 90% of "encounter" contacts are 50 s or longer, but 90% of the "not moving" contacts are 100 s or longer. Based on our 802.11a measurements in Section II, such contacts would allow a throughput of roughly 78 MBytes (or more) per "encounter" respectively 155 MByte (or more) per "not moving" contact in 9 out of 10 contacts. This example shows how big the influence of the contact situation on the performance can be. It also demonstrates the potential of the results for routing decisions.

Another interesting conclusion can be drawn from these results. As stated in equation 4, it can be expected, that "intersection" contacts are $\sqrt{2}$ times as long as "encounter" contacts. This is approximately confirmed by the results in

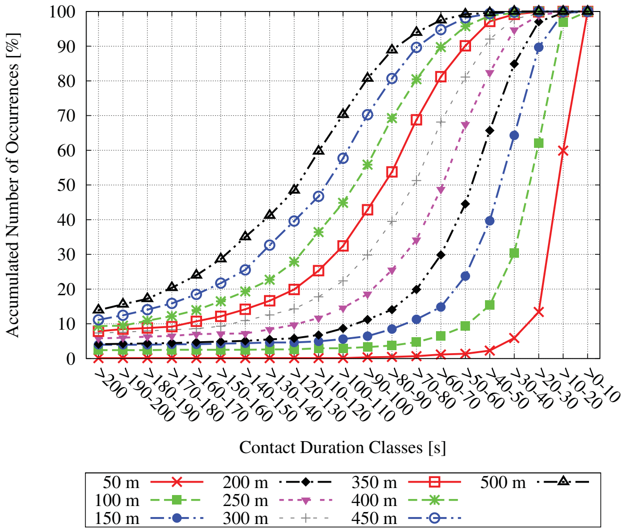


Figure 14. CDF of contact durations in class "encounter" over ranges from 50 m to 500 m

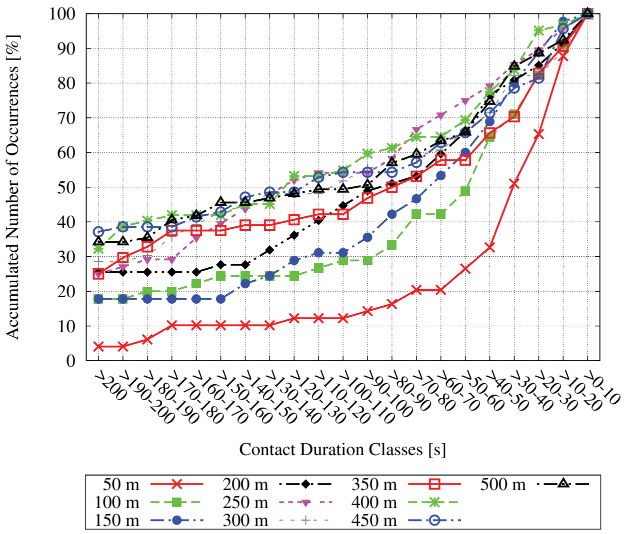


Figure 15. CDF of contact durations in class "following" over ranges from 50 m to 500 m

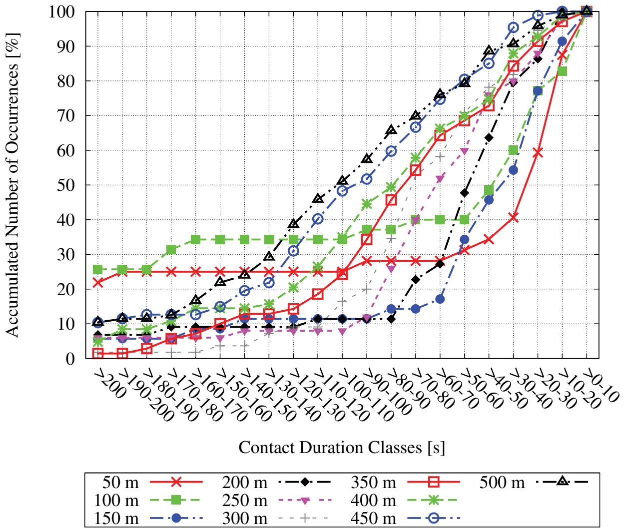


Figure 16. CDF of contact durations in class "intersection" over ranges from 50 m to 500 m

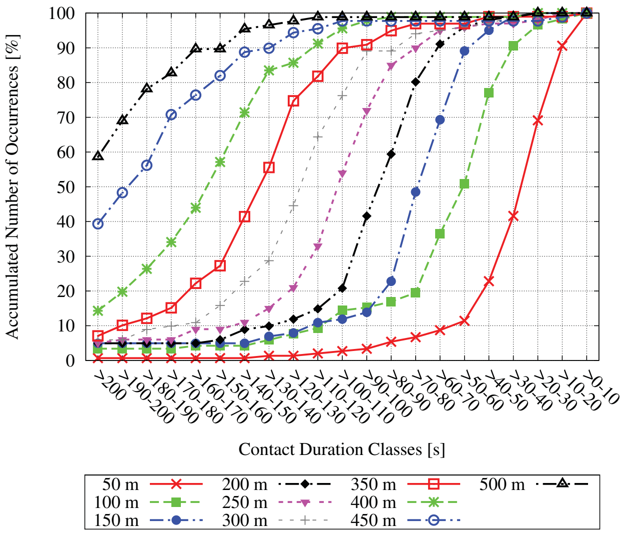


Figure 17. CDF of contact durations in class "not moving" over ranges from 50 m to 500 m

figure 13. For a range of 100 m, the median duration of "intersection" contacts is 32 s while the median duration of "encounter" contacts is 20 s. This is a ratio of 1.6. For a range of 200 m, the ratio is 1.35 while $sqrt(2) = 1,414$.

C. Verification of the analytical model

Looking at the expected growths of the contact duration according to our theoretical analysis from section V-A shows that in all described situations contact time should increase linearly with increasing range. To validate our analytical model, we have first calculated the relative growth of the median contact duration for each contact type over increasing ranges. Then, we have normalized this value according to the relative growth of the range. Intuitively, this means that a normalized relative growth of 1 resembles a growth of the median contact duration with the same ratio as the range has increased in one step. Figure 19 shows the result of our analysis. Especially "encounter" and "not moving" situations show a high variance in growth of median contact duration with changing ranges but still are within 10% of the expected value. "Intersection" and "ambiguous" contacts show the most stable dependency between range and contact duration, although it is slightly lower than expected. "Following" contacts depend less than linear on the range for ranges $\leq 300\ m$ and show almost expected behavior for ranges $> 300\ m$.

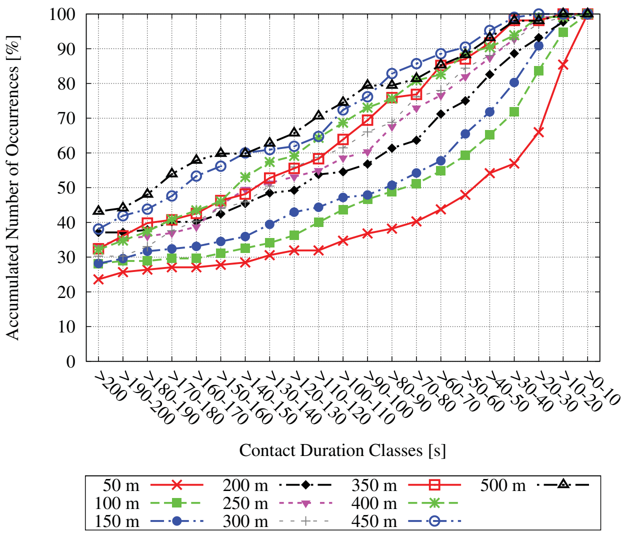


Figure 18. CDF of contact durations in class "ambiguous" over ranges from 50 m to 500 m

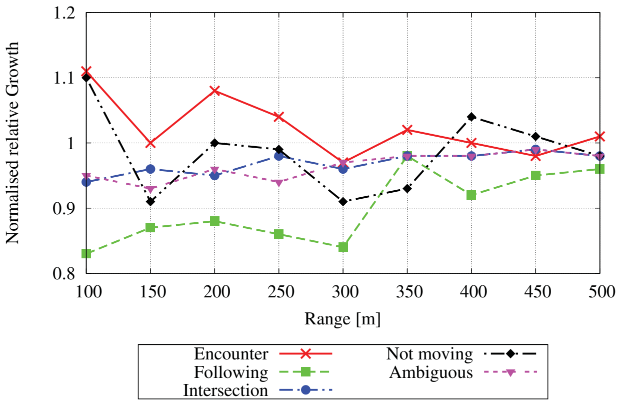


Figure 19. Growth of median contact durations over range normalized using growth in range

VI. Conclusion and Future Work

In this paper we have presented an analysis of contact duration and contact characteristics in bus-based DTNs. Our approach of using mobility traces of real buses and a DTN simulator allows the realistic simulation of different ranges. The simulation results provide important information on the expected performance of bus-based DTNs. We also characterized different classes of contact situations and demonstrated how significantly different the probability distribution of contact durations in divergent contact situations is. The results and the accumulated probabilities of different contacts allow the prediction of contact duration, which is required for capacity planning and also helpful for routing decisions. Moreover, QoS scheduling and prioritization benefit from duration prediction. We have presented a simplified theoretical model for contact durations and have evaluated its applicability in practice. Moreover we quantified the effect of radio range on contacts.

The classification of contacts is promising for the development of "duration-aware" DTN routing algorithms. Our main contribution is showing that this classification is possible by relatively simple criteria like contact angle. In future work we will investigate if a combination of angle and vehicle velocity can be used for a more granular classification, and derive a prediction model of contact duration in bus-based DTNs. Moreover, we will investigate how the amount of contacts in the "ambiguous" class can be reduced. Our future work will also examine if the classification can be applied more widely, i.e. to vehicular DTNs in general.

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