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Comparison of Routing Protocols and Communication Interfaces for the Implementation of Collision Avoidance Capabilities in Fleets of Industrial Mobile Robots

Alessandro Bonetti [*] **Lorenzo Sabattini** [*]

[*] *Department of Sciences and Methods of Engineering, University of Modena and Reggio Emilia, Italy*
{alessandro.bonetti,lorenzo.sabattini}@unimore.it

Abstract:
In this paper a novel approach to a collision avoidance system between forklifts based on a wireless communication is proposed in order to test its performance and feasibility. First of all an overview on collision avoidance systems between vehicles inside warehouses is introduced with their main advantages and disadvantages. Then the reasons that led to the study of the new solution proposed in this article are motivated. Subsequently, a brief survey on mobile ad hoc networks and their main routing protocols that allow multi-hop communication is presented. For the implementation of the simulations OMNeT++ and SUMO software were used, which allowed to develop the model and the warehouse scenarios. Furthermore, we report the collision avoidance algorithm used in this study for the generation of a plausible network data load in order to collect and analyze simulation statistics. In particular, two applications have been developed, DiscoveryApp and AnticollisionApp, which are run by each node. Several simulations were then carried out, varying the size of the scenario, the communication interface standards and the routing protocols. In particular, communication interfaces based on the IEEE 802.15.4 and 802.11g standards and AODV, DSDV, GPSR routing protocols were tested. The last part of the paper concerns the analysis of the results based on the metrics of average end to end delay, overhead, average goodput and packet delivery ratio in order to determine the best combination of technologies for an application of this type.

Keywords: Networked robots; Transport and delivery robots; Mobile robots and vehicles; Communication among robots; Industrial logistics.

1. INTRODUCTION

A topic of utmost importance in the international scene of transport and logistic is the research on the safety of forklifts, as they are one of the most dangerous type of vehicles for material handling. In fact, the US Bureau of Labor Statistics reports that around 85 fatal and 7,000 non-fatal forklift-related accidents occur each year in the US alone (U.S. Bureau of Labor Statistics, 2019). In addition to the disastrous human cost, these situations also generate a significant economic cost for companies: an accident in a warehouse can cause damage to goods and an interruption in service. For this reason it is necessary to develop active systems capable of avoiding collisions within warehouses. In contexts where manual forklifts and autonomous vehicles and mobile robots operate without the support of a fixed infrastructure, it is necessary to implement a decentralised system. In this case, vehicles are usually equipped with radar and sensor systems. For example, they can be fitted with a UWB modules (Monica and Ferrari, 2016) or laser scanners and sonars (Yuste et al., 2010) to prevent collisions. However, these solutions do not work in the case of blind spots that can be created near the intersections between racks. A way to solve this problem is presented in this article. In fact, the implementation of a MANET (Mobile Ad hoc Network) with collision avoidance purpose can work near intersections where shelves and goods block the line of sight of vehicles. Wireless signal can penetrate certain objects (Golubeva et al., 2018) and, in case it fails, other nearby vehicles can be used to transmit the information toward the destination. This technology is widely studied in the automotive sector for the implementation of ITS (Intelligent Transportation System) (Qureshi and Abdullah, 2013). In particular, collision avoidance applications (Kumar et al., 2015; Kausar et al., 2012) or other services can be implemented using a VANET (Vehicle Ad hoc Network), which is a subcategory of MANET consisting of cars as nodes. MANET and VANET technology is also spreading to other sectors such as mining (Chehri et al., 2020) and, for this reason, it was decided to test the performance and feasibility of a collision avoidance system based on a mobile communication between forklifts and automated vehicles in warehouse scenarios. To achieve this objective, two applications called

DiscoveryApp and AnticollisionApp were developed. They implement a collision avoidance algorithm, based on the communication between vehicles, which allowed the collection of simulation statistics to study the performance of the network. Subsequently, two warehouse scenarios of different sizes and with a different number of vehicles in operation were modelled and simulated using OMNeT++ and SUMO software.

The main contribution of this paper is then in the extensive comparison among different routing protocols and communication interfaces, to be exploited in industrial contexts for the implementation of collision avoidance functionalities among vehicles, including manual forklifts, automated guided vehicles and mobile robots in general.

The rest of the paper is organized as follows. Background notions on communication infrastructures, technologies, and methodologies are provided in Section 2. The proposed collision prevention algorithm is then presented in Section 3. The implementation details and the results of the simulations are then discussed in Section 4. Finally, concluding remarks are given in Section 5.

2. BACKGROUND ON COMMUNICATION INFRASTRUCTURES AND METHODOLOGIES

In telecommunication, a **MANET** (Mobile Ad hoc NETwork) is defined as an autonomous system of mobile routers and of their associated hosts connected through wireless links. In a MANET, nodes are free to move arbitrarily and are able to communicate with each other without fixed infrastructure. For this reason, mobile ad hoc network management needs to be distributed between nodes so the entire system is able to self configure and organize. The NICs (Network Interface Controllers) used for the implementation of a MANET belong to the IEEE 802.15.4 and IEEE 802.11 standards. Specifically, this article will compare the performance of IEEE 802.15.4 at its maximum bit rate of 250 kbps and IEEE 802.11g at different bit rates.

Ad hoc routing protocols are used to enable multi-hop communication and route packets to the correct destination using forwarding nodes. There are different types of ad hoc routing protocols for MANET and they are mainly classified into *topology based* and *position based*.

A topology based routing protocol uses network topology information and shortest path algorithms to define the best path in order to reach destination node. They could be classified in:

- **Proactive**: a proactive routing protocol involves a continuous exchange of data between network nodes in order to constantly update the routing tables towards each possible destinations. **DSDV** (Destination-Sequenced Distance-Vector) (He, 2002) is an example of such protocols.
- **Reactive**: reactive protocols, also referred to as “on demand driven”, create a path only when a node requires it. So, a route discovery procedure starts and allows the source to find and define a route toward a certain destination. Once completed, the involved nodes check and handle disconnections through route maintenance strategies. The most famous reactive protocol is **AODV** (Ad-hoc On-demand Distance Vector) (Das et al., 2003).

Position based routing protocols use the location of nodes to forward packets and do not take into account information on topology network and routing tables. When a node decides to send a message, the position of the destination is entered inside the packet header: it is used by the various intermediate routers to correctly re-transmit the packet toward the right geographical direction. To work properly, these protocols need the implementation of localization systems and services, which can be of different categories. **GPSR** (Greedy Perimeter Stateless Routing) is an example of position based routing protocol (Karp and Kung, 2000).

In this paper AODV, DSDV and GPSR routing protocols have been tested, and their performance evaluated using the metrics defined hereafter.

2.1 MANET metrics used in simulations

Several metrics are used to evaluate the performance of MANET (Bambrik and Didi, 2015; Ballav, 2015; Khairnar and Kotecha, 2013; Fazeldehkordi et al., 2016). In this article, the following will be studied:

- **Average End to End Delay** (Average EED) is the average time it takes for a unicast packet to arrive from the source node to the destination node within the network.

$$Average\ EED = \frac{\sum_{i=1}^{n} RT_i - ST_i}{n} \quad (1)$$

  where RT_i is the reception time of the i-th unicast packet, ST_i is the send time of the i-th unicast packet, and n is the total number of received unicast packets.
- **Packet Delivery Ratio** (PDR) is the ratio between unicast packets arriving at their destination and those sent. This metric is usually expressed as a percentage and represents the reliability of a mobile network.

$$PDR = \frac{n}{m} \quad (2)$$

  where n is the total number of received unicast packets and m is the total number of sent unicast packets.
- **Overhead** expresses the resource usage in term of throughput used for the implementation of protocols. It is defined as the ratio between the information bits used by the various protocols and total bits exchanged within the network and it is calculated as follows:

$$Overhead = \frac{TIR - TPR}{TIR} \quad (3)$$

  where TIR is the total bits of information received by MAC from lower layer and TPR is the total bits of payload received by all nodes during the simulation.
- **Average Goodput** represents the amount of useful data transferred in the unit of time on the communication channel and is measured in bit/s. It is obtained from the total throughput by discarding the overhead information:

$$Average\ Goodput = \frac{\sum_{k=1}^{p} PS_k}{ST} \quad (4)$$

where PS_k is the size in bytes of the k-th received payload, p is the total number of received payloads and ST is the total simulation time.

3. COLLISION PREVENTION ALGORITHM

This section presents the collision avoidance algorithm implemented with the purpose of generating a plausible data traffic for testing and comparing the system performance. In particular, the algorithm is composed by two applications called DiscoveryApp and AnticollisionApp which are executed by each node belonging to the distributed network.

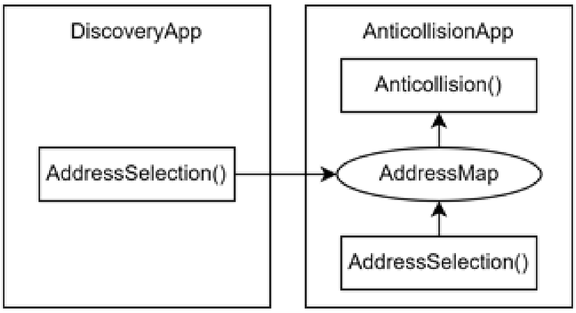

Fig. 1. DiscoveryApp and AnticollisionApp Diagram

In the following, we will assume vehicles to be modeled as points moving in a two-dimensional environment. This assumption is justified by the fact that we are focusing on the performance of the communication protocols, which are not directly influenced by the kinematics of the vehicles. Furthermore, it is assumed that forklifts are able to localize themselves absolutely within the environment.

3.1 DiscoveryApp

DiscoveryApp deals with the discovery of the neighborhood and the selection of potentially dangerous forklifts. For this purpose, at regular intervals of time, each node sends a broadcast packet containing its position and speed which is retransmitted with a TTL (Time To Live) equal to 2 hops. This information is used by the receivers to evaluate the possibility of collision using the AddressSelection() function. If this situation is detected, the sender IP address and its associated information are sent to AnticollisionApp.

3.2 AnticollisionApp

AnticollisionApp implements the following functions:

- AddressMap update and management
- sending packets
- mobility handling
- intersections handling

This application is based on a map called AddressMap which associates the IP addresses of dangerous nodes with the following information:

- Insertion time
- X position
- Y position
- X speed
- Y speed

The first operation performed is the check and removal of nodes characterized by obsolete information within the map, comparing their insertion time with the current simulation time. Next, the application uses the information about the remaining nodes to assess the presence of impending collisions and control the vehicle mobility accordingly to avoid them. Then AnticollisionApp proceeds with the transmission of unicast packets containing the position and speed of the forklift truck to the map nodes. This communication is characterised by a higher sending frequency than that of DiscoveryApp in order to make the system more reactive only when necessary. In fact, only the nodes involved in potentially dangerous situations exchange information at high frequency and therefore no bandwidth is wasted on the communication channel. Vehicles receiving these packets use the information contained therein to update their AddressMap data regarding the sender node.

In the following subsections, the AddressSelection() and AntiCollision() methods are briefly described to clarify the operation of the two presented applications.

3.3 AddressSelection()

The address selection method is used by each node to evaluate the possibility of collision with the vehicle from which a packet has been received (both broadcast and unicast) using information relating to the two forklift trucks involved. The function returns a boolean variable: if it is true the sending node and the information associated with it are inserted or updated (if already present) in the AnticollisionApp address map. Otherwise, if the method returns false, the node is deleted. The operating principle of this method is based on the use of positions and speeds to define the straight trajectories of the forklifts and on a distance threshold called DistanceUnicast within which the sending node is considered dangerous. Based on the different situations that may occur, different cases (7) of collision risk assessment can be distinguished:

(1) the two forklifts move along coincident lines, they follow each other and their distance is less than the DistanceUnicast threshold.
(2) the two forklifts move along coincident lines, they are directed towards each other and their distance is less than the DistanceUnicast threshold.
(3) the two forklifts move along close parallel lines, they follow each other and their distance is less than DistanceUnicast.
(4) the two forklifts move along close parallel lines, they are directed towards each other and their distance is less than DistanceUnicast.
(5) the nodes move along intersecting lines, both are directed towards the intersection point and their distance is less than DistanceUnicast.
(6) the receiver node moves and the sender is stationary, their distance is less than DistanceUnicast and the distance between the straight trajectory of the first

and the point relative to the position of the second is less than a forklift width.

(7) the sending node moves and the receiver is stationary, their distance is less than DistanceUnicast and the distance between the straight trajectory of the first and the point relative to the position of the second is less than a forklift width.

3.4 AntiCollision()

The anti-collision method() deals with controlling the mobility of each vehicle in order to avoid potential collisions. Its operating principle is based on the constant updating of a variable called vehicle_state. It can take on three different values, each of which is associated with a mobility state of the forklift:

- **3** ⇒ the forklift can move freely;
- **2** ⇒ alert state in which the forklift can move with maximum speed reduced to 1 m/s;
- **1** ⇒ stop state in which the vehicle must stop.

When the function is called, the vehicle_state is set to three. Then the node scrolls through its AddressMap and uses the information relating to the position and speed of each vehicle to appropriately update the variable value. In this regard, at each cycle its value can only be confirmed or decreased so that the most dangerous conditions take precedence for the management of the forklift mobility.

4. IMPLEMENTATION AND VALIDATION

In this article, two different warehouse scenarios are modelled using the simulation software SUMO (Behrisch et al., 2011) and OMNeT++ (Varga and Hornig, 2008). The first one is a vehicle mobility simulator that allows to define the characteristics and routes of the forklifts. The second one is a telecommunication network simulator that is used to simulate MANET and allows modelling the dielectric and reflection losses caused by the presence of shelves and goods placed in the two scenarios. Specifically, the two warehouses have the following characteristics:

Scenarios	small	big
surface $[m^2]$	65*100	136*120
number of forklifts	12	22
simulation time [s]	1200	600

As shown in Fig. 2, for both scenarios, two different configurations of time intervals for sending packets by the DiscoveryApp and AnticollisionApp applications were tested.

For each configuration, different communication standards and routing protocols were tested by collecting data and calculating the metrics presented in subsection 2.1. Specifically, overhead was only used in comparisons between routing protocols in order to analyse their use of network resources. In the next subsections, three significant simulations will be presented to analyse the performance of the collision avoidance system.

4.1 Sim1

The first simulation concerns a comparison between the IEEE 802.15.4 and 802.11g communication standards with

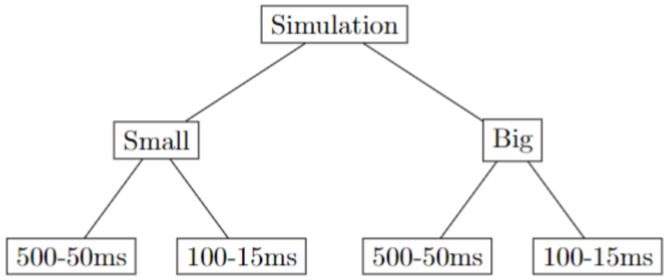

Fig. 2. Simulation tree diagram: both small and big scenarios were simulated in two configurations of time interval of sending DiscoveryApp and Anticollision-App packets.

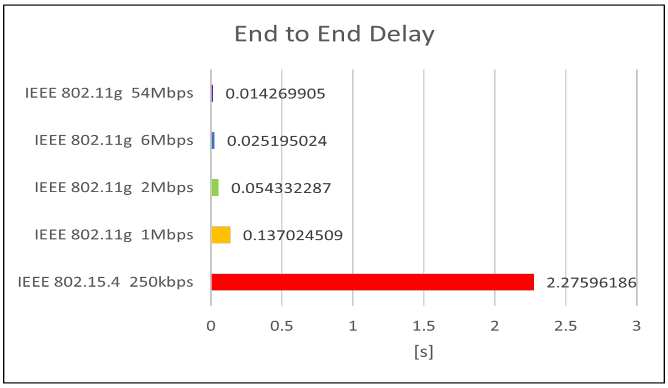

Fig. 3. Average EED measured in four tests developed with a varying network interfaces and bit rates

different data rates. This scenario is the one with the lowest network load. In fact, the system is simulated in the small warehouse where there are fewer forklifts communicating with each other with a DiscoveryApp and AnticollisionApp packet sending time interval of 500 ms and 50 ms respectively. The payload size for both applications, as in all other simulations, is 80 bytes.

Scenario	Small
T_DiscoveryApp	500 ms
T_AnticollisionApp	50 ms
Routing protocol	AODV
Payload size	80 bytes

Regarding the average end to end delay, it can be observed in Fig. 3 that the IEEE 802.15.4 standard is characterised by values that are too high for the collision avoidance application. The 802.11g standard, on the other hand, performs adequately and meets the specification of 100 ms (set as acceptability threshold for this study) for bit rates above 1 Mbps, with the best result recorded for 54 Mbps.

Referring to Fig. 4, the packet delivery ratio of IEEE 802.15.4 is characterised by a value of less than 0.5. This is probably due to a saturation condition of the network resulting in node queues being filled and obsolete packets being dropped. On the other hand, the IEEE 802.11g interface is characterised by a high PDR value for all the studied cases.

As shown in Fig. 5, average goodput performance is stable above 2 Mbps. For the IEEE 802.15.4 standard, it shows

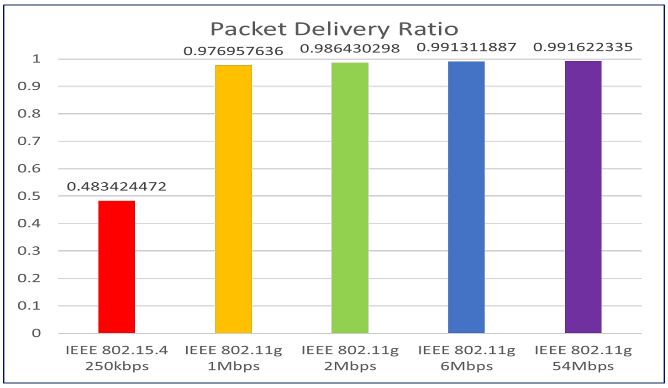

Fig. 4. PDR measured in four tests developed with a varying network interfaces and bit rates

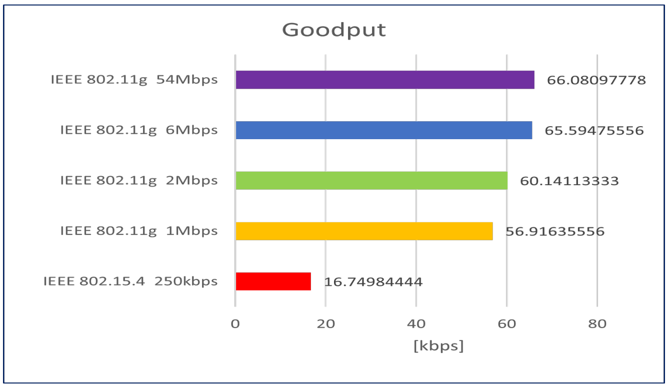

Fig. 5. Average goodput measured in four tests developed with a varying network interfaces and bit rates

much lower values than the other cases studied because bandwidth saturation conditions occurred.

4.2 Sim2

In this simulation, the routing protocols AODV, DSDV and GPSR are compared in order to analyse which of them provides the best performance. The 54 Mbps IEEE 802.11g standard is set as the communication interface since it has proven to be the best in all network interface comparisons. The hello/beacon messages of DSDV and GPSR required for the implementation of their operation strategy are sent at regular intervals of 500 ms duration.

Scenario	Big
T_DiscoveryApp	100 ms
T_AnticollisionApp	15 ms
NIC	IEEE 802.11g @ 54Mbps
Payload size	80 bytes

As regards average EED, it can be observed in Fig. 6 that all three routing protocols respect the 100 ms threshold and are therefore suitable for this collision avoidance application.

In Fig. 7 ,the packet delivery ratios obtained by simulating the three routing protocols are practically identical with a value of about 0.97, which is a very good result for the application context dealt with in this research.

The average goodput values of the three routing protocols show, in Fig. 8, minimal differences between them due to

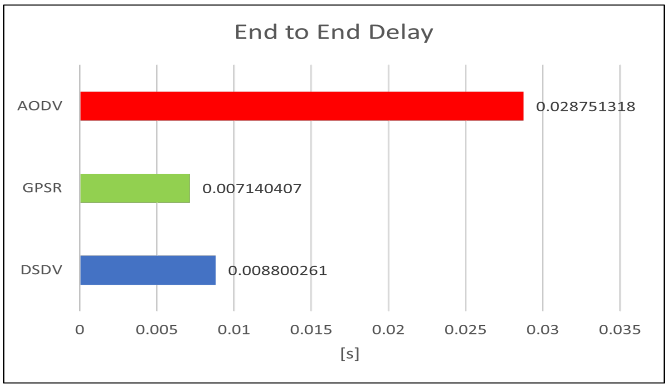

Fig. 6. Average EED obtained by simulating different routing protocols

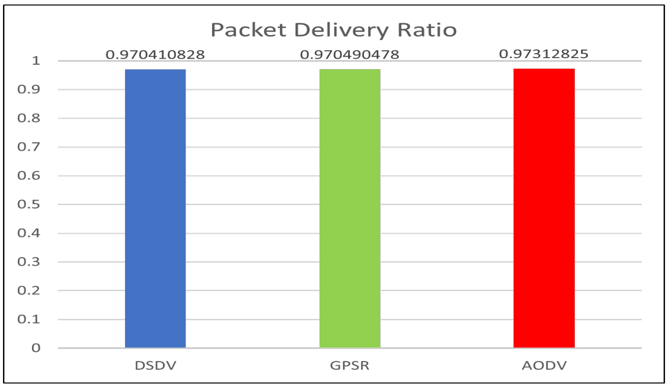

Fig. 7. PDR obtained by simulating different routing protocols

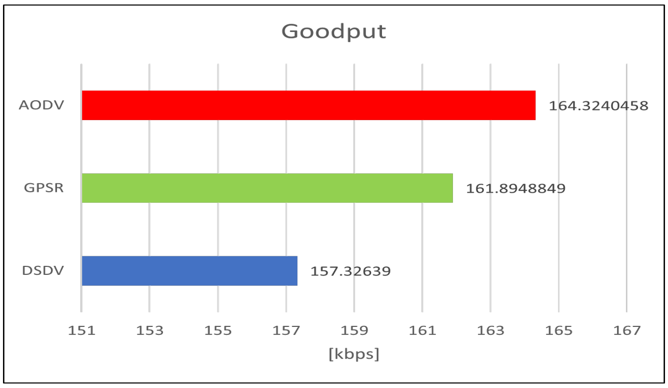

Fig. 8. Average goodput obtained by simulating different routing protocols

small variations recorded during the simulation caused by their different operating principles.

Looking at Fig. 9, the overhead of DSDV is characterised by higher values than the other two. This is due to the flooding mechanism that is activated when a link between two nodes is broken.

4.3 Sim3

In the following simulation, the performance of the routing protocols is analysed in the large warehouse scenario where 22 forklifts are operating and communicating with each other with a packet sending rate of 100 ms for Discov-

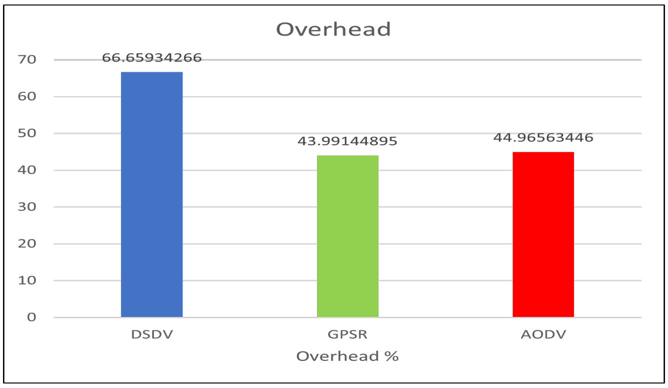

Fig. 9. Overhead obtained by simulating different routing protocols

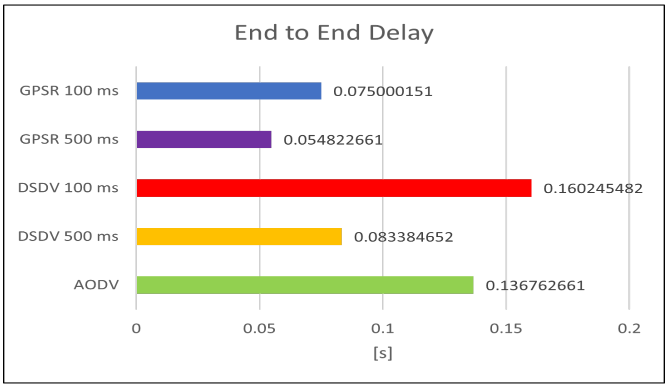

Fig. 10. Average EED measured in simulations of different routing protocols with different configurations

eryApp and 15 ms for AnticollisionApp. The vehicles are equipped with communication interfaces based on IEEE 802.11g standards with a bit rate of 54 Mbps, for the reasons expressed in the previous section. Both DSDV and GPSR, as for the small scenario, are tested in two different configurations: the first one involves sending hello/beacon messages every 500 ms and the second one every 100 ms. In this way, it is possible to study how different settings of the protocols affect the performance of the system. The table below shows the parameters used.

Scenario	Big
T_DiscoveryApp	100 ms
T_AnticollisionApp	15 ms
NIC	IEEE 802.11g @ 54Mbps
Payload size	80 bytes

Referring to Fig. 10, all the average end to end delay values have undergone a significant increase compared to those obtained in the previous simulations and only in three cases the 100 ms threshold is respected: those relating to DSDV 500ms, GPSR 100ms and GPSR 500ms.

The PDR is characterised by a low value for each simulated case, as shown in Fig. 11. The worst performance was obtained with the DSDV protocol at 100 ms and this is probably due to network saturation conditions that occurred during the simulation. The best results were achieved by GPSR, which recorded a packet delivery ratio of over 0.9 in both configurations.

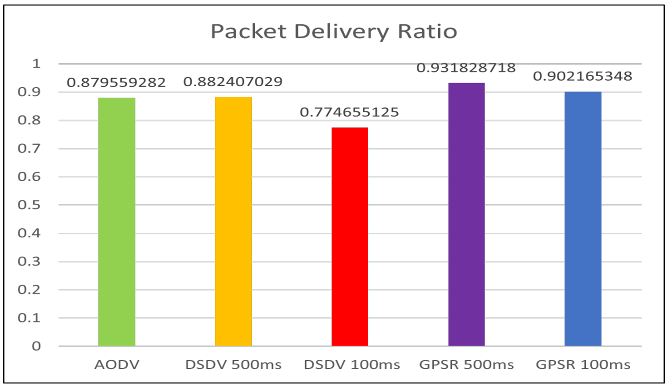

Fig. 11. PDR measured in simulations of different routing protocols with different configurations

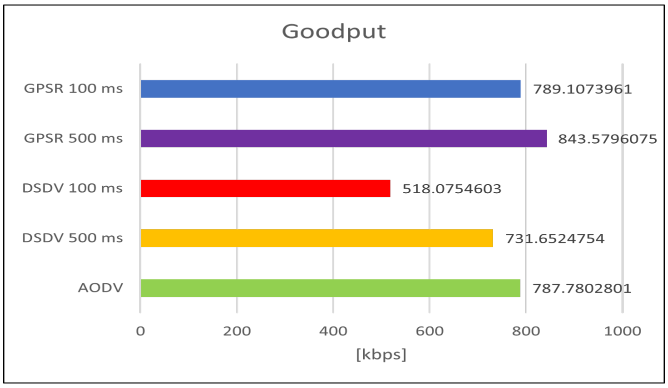

Fig. 12. Average goodput measured in simulations of different routing protocols with different configurations

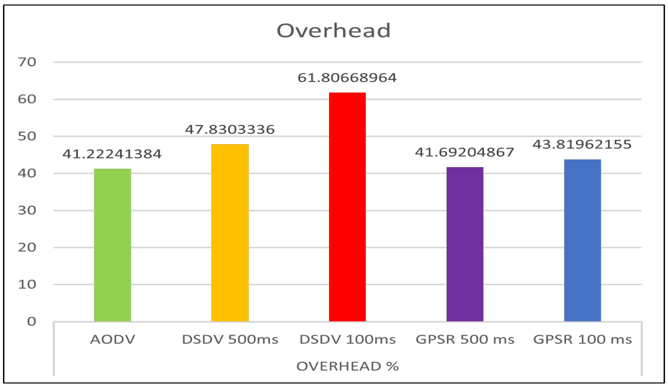

Fig. 13. Overhead measured in simulations of different routing protocols with different configurations

In Fig. 12, the average goodput obtained with the DSDV 100 ms routing protocol has a significantly lower value than in the other cases. This confirms the network overload hypothesis expressed in the PDR analysis.

The overhead values calculated for the different routing protocols are shown in Fig. 13. As can be seen, the proactive operating principle of DSDV makes greater use of the throughput available for its implementation.

4.4 Discussion

As regards the communication interfaces, it has been seen that the IEEE 802.15.4 standard is absolutely not suitable for the collision avoidance application even in the context characterized by the lowest network load. This technology has an insufficient data rate of 250 kbps which causes high latency and a low packet delivery ratio performances.

The results related to the standard IEEE 802.11g showed that it is suitable for system implementation in most cases. The only simulations in which some criticalities have occurred are those characterized by higher sending packet frequency in large warehouse scenario. In this context it may be convenient to adopt more recent standards with MIMO technology to implement multi-stream propagation and beamforming techniques. In this way, by using more antennas for each router, a more reliable data transmission and an increased bandwidth are obtained by using spatial multiplexing. In summary, IEEE 802.11g is suitable for the development of an collision avoidance system based on a communication between forklifts and is characterized by excellent performances regarding latency and packet delivery ratio. However, in the case of dense networks with a high data flow it is preferable to focus on more modern technologies.

With regard to routing protocols, we have seen how AODV (reactive) does not represent the best choice for a collision avoidance system because of its higher communication latency than the proactive or position-based types. On the other hand, a positive factor of AODV is its reduced overhead, which allows its implementation in those contexts where a limited data rate is available.

The DSDV proactive protocol records low average end to end delay in most simulations and a good performance in terms of packet delivery ratio. The overhead is significantly higher than with other routing protocols but, if a high-speed communication interface is used, this is not a problem. The only contexts in which network overloads have been recorded with DSDV are those characterised by a high vehicular density and a high rate of data exchange. In these cases it might be convenient to use a position-based protocol such as GPSR which has shown very good results in simulations. However, it must be said that in this research it was not possible to develop a localisation service, which is essential for the functioning of the protocol. In fact, in the implementation of GPSR on OMNeT ++, each sending node knows in advance the position of the trolley with which it intends to communicate. In a real system this cannot be taken for granted and this information can only be obtained by means of a Location Service (LS) mechanism. For this reason, the GPSR performance shown in this article may not be reliable. Further studies have to be developed in order to gather more information about the impact of a LS implementation.

Finally, again with regard to routing protocols, it has been shown that correct setting of the properties and characteristics of DSDV and GPSR can have a significant impact on system performance. The most suitable settings for a specific real-world context can be found by using the OMNeT++ simulator or by using a test bench.

5. CONCLUSION

In this paper, a simulation methodology for mobile ad hoc networks composed of forklifts has been presented. In particular, the modelling process of two warehouse scenarios has been described in order to evaluate the performance of a communication system between vehicles, used for collision avoidance purposes. The simulations showed that, by equipping the vehicles with NICs based on IEEE 802.11g standards, it is possible to obtain a communication latency and a packet delivery ratio suitable for the application. On the other hand, the IEEE 802.15.4 standard is inadequate due to its low bit rate.

When analysing the performance of the different routing protocols, DSDV and GPSR performed better than AODV in terms of average end to end delay and packet delivery ratio in low and medium network load cases. In the most onerous simulation in terms of network resource usage, however, none of the three routing protocols achieved a performance suitable for a collision avoidance system. Moreover, it was seen that a procedure for setting up the operating parameters of the protocols is necessary to achieve better performance.

In future work, to demonstrate the reliability of the model and validate the results, a real test-bed could be implemented using Raspberry Pi boards installed on-board vehicles. These are single-board computers equipped with a communication interface based on IEEE 802.11 a/b/g/n/ac standards on which it is possible to install a Linux operating system and to implement an ad hoc connection mode (Sati and El-bareg, 2018).

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