Analysis of methods for prioritizing critical data transmissions in agricultural vehicular networks

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***Abstract*—Applying wireless communication technologies to agricultural vehicular networks often results in high end-to-end delays and loss of packets due to intermittent or broken connectivity. This paper analyses the methods for the successful delivery of the vehicular data within acceptable delay times. Different kinds of data that are generated and transmitted in agricultural networks are considered in this paper, followed by the data prioritization methods which allow critical data to be prioritized against other data. In this regard, Enhanced Distributed Channel Access, Differentiated Services, and application-based data rate variation are discussed in conjunction with the Simple Network Management Protocol. These techniques are simulated or tested separately and then together and the results show that even in poor network conditions, high-prioritized data is not lost or delayed.**

***Index Terms*—DiffServ, EDCA, agricultural vehicular network, prioritization.**

I. Introduction

In the era of intelligent machines and autonomous vehicles, reliable communication takes a major role. In an agricultural scenario, failure in transferring vital information between machinery can result in faulty operation or even loss of machinery. Hence, most of the agricultural machinery used with a master vehicle, e.g. a tractor and an implement, still uses wired communication. Another major reason for using wired communication is the variation in wireless network performance depending on the distance and the changing environment, which results in a decrease of Quality of Service (QoS). But with the vast developments in the wireless networking (e.g. IEEE 802.11b/g/n/ac/ax standards [1], [2]) agricultural networks can utilize wireless technologies to connect vehicles without worrying about vital information loss due to low QoS. In addition, for the communication between independently moving vehicles e.g. tractor and a harvester, wired communication is not possible.

To solve these issues, this paper analyzes multiple techniques for the successful data communication using WLAN. This paper also investigates the different types of application data and prioritizes them based on their importance. As the data prioritization based on the information identity [3] is realized in Delay Tolerant Networks and Wireless Sensor Networks [4], the principle may also be adapted for the Agricultural vehicular networks to optimize the network's functionality. This paper presents:

- Classification of the agricultural data in the area of field-cultivation.
- QoS support of agricultural vehicular networks on MAC, network, and application layer.
- Integration and evaluation of multi-layer QoS support for agricultural networks.

The applications running on agricultural machinery generate various kinds of information, often burdening the network, bringing in the need for classification of data. In such a scenario, channel access becomes a challenge for applications sending crucial data. Furthermore, a saturated network core e.g. routers, due to multiple high data rate applications, requires prioritized forwarding at the network layer. The MAC layer QoS method presented in this paper resolves the issue of competing channel access. The network layer QoS using data prioritization addresses the network core issues. Combining MAC and network layer QoS with intelligent applications, that vary their data generation rates with the network conditions, provides a fail-safe mechanism to deliver crucial data while decreasing the resources allocated to unimportant data when needed.

The rest of the paper is organized as follows: Section II addresses the different types of data that get transmitted in the context of agricultural communication. Section III presents the different methods used to allocate network resources to agricultural data types depending on their priority. Section IV presents the simulation scenarios for these methods and their results. Then lastly, section V concludes the paper and outlines the future work.

II. Agricultural Equipment and Data Classification

Agricultural vehicles have multiple modules such as telemetry, ground sensors, mobile connectivity modules, and more. These modules communicate with each other or provide information to machine operators, therefore generating various kinds of information. The categorization of these data types is needed and is done by analyzing different scenarios. First, only two vehicles working together are considered: a harvester as a master and a utility vehicle as a slave (e.g. truck used as a storage vehicle). The harvester sends various kinds

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of information to the utility vehicle, which includes GPS coordinates, speed, the direction of movement, the distance between vehicles\objects, row spacing, and the control data. The organization of newly joining vehicles and assignments of operational tasks to them is also an important part of the operation. Thus task data and fleet coordination commands are also considered.

Audio communication between the vehicle operators is necessary and certain vehicles also need video feedback from each other. This is particularly true in the case of a harvester and a utility vehicle whose operators must have information about the remaining storage capacity of their vehicles. This is achieved with a camera that overlooks the storage area of the vehicle. A typical agricultural video feed has a relatively small frame size of 320x240 pixels with up to 15 fps. In [5], it is shown that 1.12 Mbps are required for a 320x240 resolution 25 fps video stream. Thus, audio communication and video streams have to be added in the data types list along with software updates, diagnostic data, log data, and the precision farming maps.

Due to the high variety of data types, classification is needed based on the importance of data. For classification, three agricultural equipment manufacturers who are also part of the Agricultural Industry Electronics Foundation (AEF [9]) were consulted, and the following classification of data types was validated by them. AEF works on unifying wired and wireless agricultural equipment connection interfaces e.g. High-speed ISO-Bus [10], thus the latency and data rate requirements mentioned in II-A are recommended by them.

A. Classification of Agricultural Data

Data types that are needed for the proper functioning of the vehicles are essential, while other data types are not. Therefore, prioritization becomes crucial. Similarly, data types have different data rates and latency requirements.

1) High Priority: High priority data is required for the workflow operation and directly affects the efficiency of the vehicles and machines. Data types that belong in this category are task data, control data, GPS position, speed, the direction of vehicle, and row spacing. The minimum requirements for latency and data rate for these data types are

- Max. latency: 100 ms
- Min. data rate: 50 Kbps

2) Medium Priority: Medium priority data is mainly assisting data for the operators. Without it, tasks could be significantly delayed. The machine diagnostic data, process data exchange, audio/video communication, and the fleet coordination commands are prioritized as of medium priority. Machine diagnostic information is used to diagnose and fix broken equipment. For medium priority data types the following requirements are given:

- Min. data rate: 500 Kbps (2 Mbps for video)
- Max. latency: 200 ms (500 ms for video)

3) Low Priority: Data types that are not critical or important for the workflow operation are placed in this category. These data types consist of software updates, map information, and logging information. Map information showing terrain height, roads, waterways, boundaries of fields, etc. are shared with the vehicle equipment before the work starts. Low priority data types have different requirements from each other. However, the transfer of these data types occurs when the equipment and machinery are not in use. Therefore, low-prioritized data may use whatever resources are unused by higher priorities at that moment. All of these requirements are up-to-date and recommended by AEF partners.

III. Prioritization methods for Data Transmissions

Agricultural data prioritization is vital when using wireless networks with agricultural vehicles because of the network condition variations due to mobility. Numerous vehicles competing for transmission makes it harder for the high priority applications to get channel access, especially in the presence of applications trying to send high bandwidth data, e.g. video. Similarly, treating packets equally can generate large delays for real-time applications e.g. audio apps, in presence of video data. In such situations, channel access prioritization and network layer prioritization in the network devices is used to ensure the timely delivery of critical data.

Enhanced Distributed Channel Access is utilized which is a MAC layer channel access coordination function. Further, Differentiated Services allow data prioritization and forwarding at the network core. Finally, for the application level prioritization, traffic configuration and SNMP are used.

A. Enhanced Distributed Channel Access at MAC Layer

Enhanced Distributed Channel Access (EDCA) creates an opportunity for the high-prioritized data to be sent earlier than the low-prioritized data by the source.

In wireless networks, multiple devices compete for channel access when they need to send the data. Similarly, multiple agricultural vehicles working together could result in insufficient channel access for the applications which have high-prioritized data to send, especially when other applications have large amounts of data to send, e.g video streams. Therefore, channel access prioritization is needed.

In WLANs, the receiving device must wait for the Short Inter-frame Space-time (SIFS) before sending back the Acknowledgement (Ack), if an Ack is required. While the receiver end waits for the SIFS duration, other devices must wait for the DCF Inter-frame Spacing (DIFS) time and some arbitrary backoff time before they can get the channel access [11]. EDCA makes DIFS time shorter for the devices which have high-prioritized data to send. MAC layer channel access protocol called Tiered Contention Multiple Access (TCMA) allows this. TCMA introduces shorter Arbitration Inter-frame Spacing (AIFS) for the devices with the high-prioritized data as shown in fig. 1. EDCA further defines a Transmit Opportunity (TXOP) period in which a device with the high-prioritized data gets contention-free access to the channel. It helps the device to send as much data as it can in that duration. For the packet sizes larger than the TXOP period, the packet is fragmented into smaller frames.

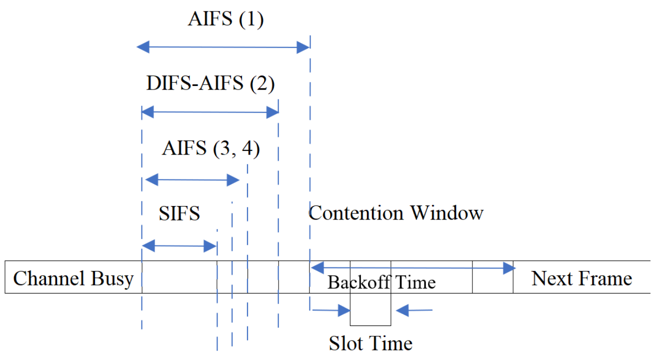

Fig. 1. Frame spacing for EDCA.

EDCA defines four different access categories, with varying contention window sizes, to classify data into multiple priority levels. The contention window's minimum and the maximum size is calculated based on traffic on the network, the modulation scheme used, and the minimum and maximum contention window size defined at the physical layer. Access categories of EDCA are as shown in the table I and the formula for calculating the window sizes are given in the table II.

TABLE I
EDCA ACCESS CATEGORIES [11]

Access Category (AC)	Designation	Priority
AC_BK	Background	1
AC_BE	Best Effort	2
AC_VI	Video	3
AC_VO	Voice	4

TABLE II
EDCA CONTENTION WINDOW BOUNDARIES [11]

AC	CW_{min}	CW_{max}
AC_BK	aCW_{min}	aCW_{max}
AC_BE	aCW_{min}	aCW_{max}
AC_VI	$(aCW_{min}+1)/2-1$	aCW_{min}
AC_VO	$(aCW_{min}+1)/4-1$	$(aCW_{min}+1)/2-1$

B. Differentiated Services

Differentiated Services provide a mechanism for classifying network traffic and provides QoS at the network layer. An agricultural scenario in which Differentiated Services is useful includes multiple vehicles communicating with a local farm server. Therefore, multiple data types and data streams have to be sent to a server that is connected to the network core via single link. A need for the queue management based on the data priority arises here. Thus, Differentiated Services are configured at all network devices to prefer high-prioritized data when forwarding the packets.

Differentiated Services use 6 bits, called Differentiated Services Code Point (DSCP), out of 8 specified bits in the IP header to assign a priority to a packet. The remaining 2 bits are used for congestion control. DSCP can further be divided into 2 groups of 3 bits each. Higher and lower order 3 bits are used to define the class and the drop probability of packets respectively.

Table III shows DSCP classes based on 3 higher order bits.

TABLE III
CLASS SELECTOR BITS OF DSCP [8]

Value	Description
000 (0)	Best Effort / Routine
001 (1)	Priority
010 (2)	Immediate
011 (3)	Flash (used mainly for Voice or for Video)
100 (4)	Flash override
101 (5)	Critical (Used for Voice with Real-time transport protocol)
110 (6)	Internet
111 (7)	Network

Table III shows that the high-prioritized data can be sent with the Priority class while the Flash class can be used for audio and video. The rest of the application data types can be sent as Best effort. The last 3 bits (Drop probability) further classify each priority class into 3 subcategories.

- 010: Low drop probability
- 100: Medium drop probability
- 110: High drop probability

Drop probability bits are used in the cases when a network is saturated with the same class data (e.g. when audio and video data is sent through the network in the same category). Video saturates the network resulting in network performance drops which causes loss of audio packets. In such a case, the drop probability is set to low for audio and high for video, thus the system will opt to drop video packets over audio packets.

C. Prioritization using SNMP and traffic configuration

The applications can be made aware of the network traffic and conditions, helping to decrease the load on the network when high-prioritized data is lost. For agricultural vehicular networks, this means that applications monitor the available data rate and latency to the destination. With this information, the source applications vary data generation rate to provide better QoS for the high-prioritized data when needed.

Simple Network Management Protocol (SNMP), mainly used for managing network devices remotely, allows a network device to query information from other devices over the network. For our use case, SNMP can be configured at the source to query the received data rate from the destination. This helps the source to decrease the data generation rate of low priority packets to allow the high priority data to pass through.

IV. SIMULATIONS AND TEST SETUP

A. Simulation Scenario for EDCA

As EDCA prioritizes at the MAC layer, it is simulated with WLAN nodes in the OMNeT++ [6] simulator. A scenario where multiple vehicles are working closely is created. This scenario corresponds to a harvester and an assistant vehicle as highlighted by the red square in fig. 2. Both vehicles connect to the access point present on the harvester. High priority data

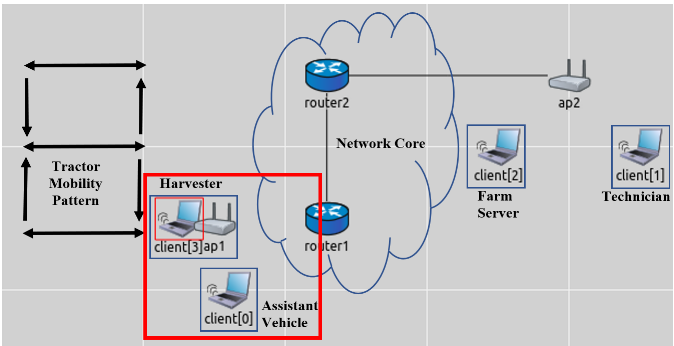

Fig. 2. Simulation Scenario.

types mentioned in section II-A1 are sent by the harvester to the assistant vehicle. The data generation rate for these data types is set to 100 Kbps with the time interval between packets set to 10 ms. Similarly, medium priority (e.g. video) data generation rate is set to 10 Mbps to saturate the network, and the time interval between two packets is set to 1 ms. Finally, for all the low-prioritized data types (e.g. production logs), the combined data rate of 1 Mbps and time interval of 10 ms is configured. Other important simulation parameters are configured as

- Simulation time: 600 seconds
- WLAN operating mode = 802.11g
- WLAN transmitter power = 100 mW
- Mobility = Tractor Mobility (shown in Fig. 2)
- Movement speed = 1 m/s

IEEE 802.11g WLAN mode is chosen due to various reasons. Some of these reasons are non-ideal antenna placement on agricultural devices, lots of metallic parts surrounding the communication devices, and varying distances between the vehicles. Due to these reasons signal quality reduces significantly. Furthermore, due to various designs of vehicles and equipment, their interference data is not available. Thus slightly older WLAN standard, i.e. 802.11g is used to reflect the real-world conditions.

1) Results: Improvement in the high-prioritized data reception rate, when the available data rate is low, is seen from Table IV.

TABLE IV
PACKET RECEPTION PERCENTAGE WITH AND WITHOUT EDCA

Packets reception %	high priority data	Medium priority data	Low priority data
EDCA Off	26.27%	26.65%	70.68%
EDCA On	99.88%	37.07%	17.73%

Comparing figures 3 and 4 shows the latency reduction when using EDCA for high priority data. Fig. 3 also show

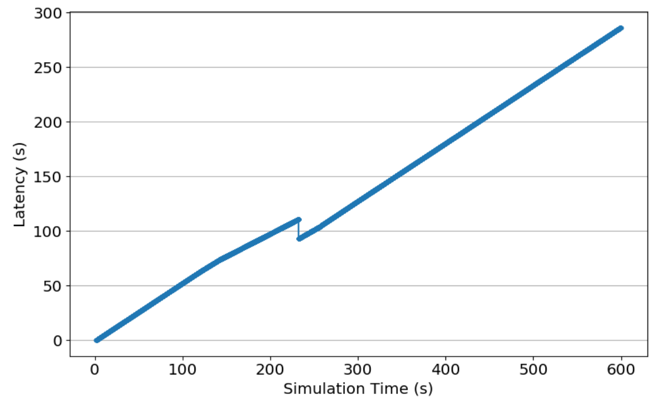

Fig. 3. High-prioritized data latency without EDCA.

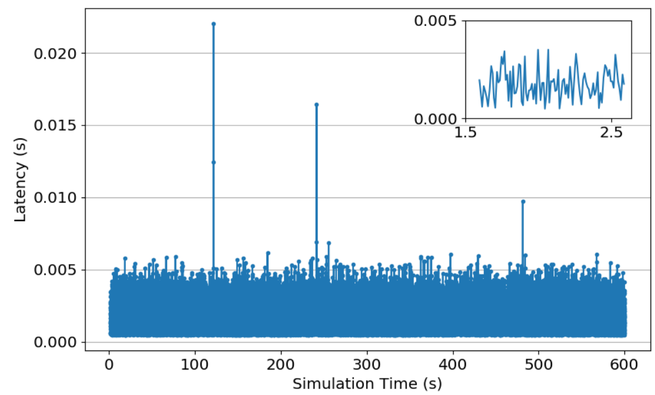

Fig. 4. High-prioritized data latency with EDCA.

zoomed version of graph from 2 to 4 seconds of the simulation. As mentioned before, the medium priority data is saturating the wireless link, thus restricting the channel access for high priority data. In such a case when EDCA is not used (fig. 3), latency for high priority data linearly increases along with the simulation time. In contrast when EDCA is implemented (fig. 4), the high priority packets are transmitted before medium and low priority packets, thus reducing the latency which was linearly increasing before.

B. Simulation Scenario for Differentiated Services

The simulation for Differentiated Services is also done with the OMNeT++ simulator. The scenario created is shown in fig. 2. A technician is added to the simulation to represent a maintenance worker. The server sends the high-prioritized task data to the harvester with a 100 Kbps data rate. Meanwhile, the harvester sends the low priority background data to the server at 50 Kbps data rate. An audio file of 50 seconds long is transmitted between the harvester and the technician with the following parameters:

- Audio file type: mp3
- Audio codec: PCM µ-law
- Sampling rate: 8000 with 8 bits/sample
- Compressed bit rate: 64 Kbps

Audio communication acts as the medium-prioritized data in the simulation. An artificial bottleneck is created in the network core, between the routers in fig. 2, to simulate the poor network conditions. The core is configured to provide only 128 Kbps and a bottleneck link is configured to reserve 50% bandwidth for high-prioritized data under load.

1) Results: Since the audio file is 50 seconds long, we show the results for this duration of the simulation.

TABLE V
PACKET RECEPTION PERCENTAGE WITH AND WITHOUT DIFFSERV

Packet reception %	**High priority data**	**Medium priority data**	**Low priority data**
DiffServ Off	28.19%	29.29%	44.09%
DiffServ On	99.97%	92.8%	18.03%

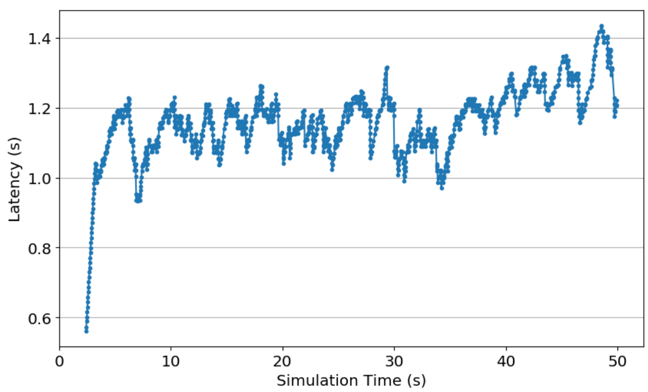

Fig. 5. High-prioritized data latency without DiffServ.

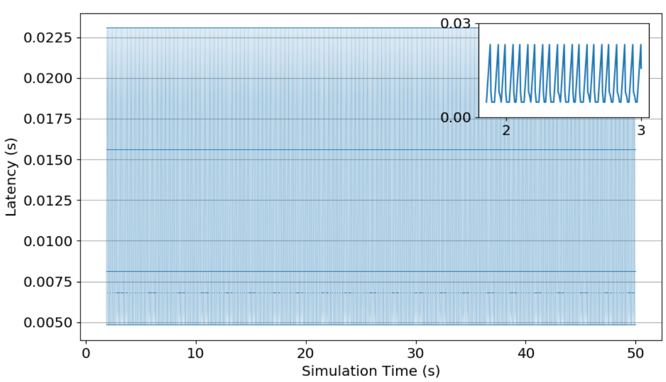

Fig. 6. High-prioritized data latency with DiffServ.

Table V shows the decrease in high-prioritized packet loss for when Differentiated Services are used. Figures 5 and 6 show the improvement in latency with Differentiated Services. While latency for consecutive packets varies between 5 ms and 25 ms (fig. 6), it is within the requirement of under 100 ms. Due to the latency for each packet being represented by a dot in fig. 6, and latency varying between 5-25 ms, multiple lines are shown. With the zoomed-in graph in fig. 6, varying latency values can be seen clearly.

C. Test scenario for SNMP

A network using netbooks equipped with WLAN is created for testing the SNMP based application data generation rate manipulation. Two netbooks are configured as a source and a destination and are connected via 2 routers in between. The maximum data rate of the network is capped to 10 Mbps. The source is configured to send the low priority video with 10 Mbps allowed data rate and the high priority packets with a 100 Kbps data rate. To further saturate the network, the source is configured to start sending the medium prioritized data with a 5 Mbps data rate in the middle of the experiment. This should force the source to decrease video traffic rate thus decreasing the video quality while maintaining the same data rate for high priority data and allocating needed bandwidth for the medium priority data. At the destination, the effective reception rate is measured for all the data types.

An SNMP manager is set up at the source which queries the destination about the current data reception rate. The destination netbook is set up as the SNMP agent responding to those queries. A python script handles all of the modifications in the traffic generation at the source. The flow diagrams of both devices are given in fig. 7.

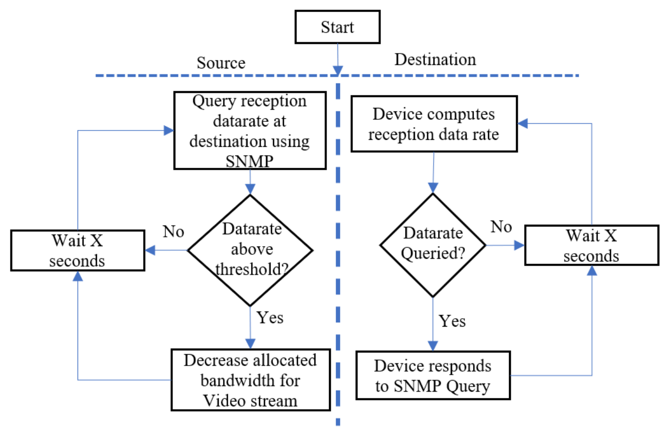

Fig. 7. Flow diagram of source and destination.

In fig. 8 it is seen that the high priority data is not affected even when the network is saturated. Furthermore, the low priority data rate is decreased when the medium priority data is needed to be sent. This verifies that SNMP feedback from the destination to the source can help in allocating the necessary bandwidth to different data priority classes at the application layer.

D. Integrated Approach

Channel access prioritization at the MAC layer using EDCA, network layer prioritization using Differentiated Services, and variable data generation rate at the application layer implemented together maintains the needed QoS for different data types in the vehicular agricultural networks. Therefore, instead of experiencing the bottlenecks for all the data types, high-prioritized applications can function continuously, and

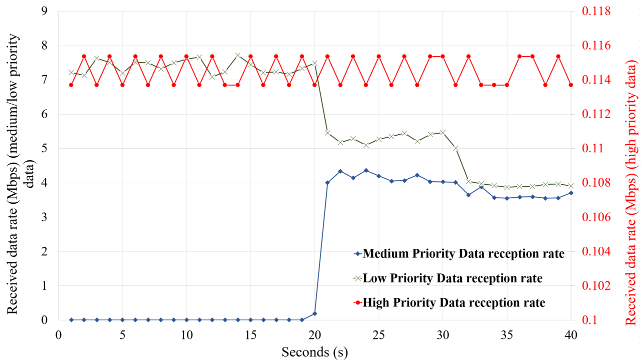

Fig. 8. Received data rate over time.

the workflow of the vehicles is not affected. MAC layer EDCA prioritization is helpful when multiple wireless devices are competing for channel access and there is a central decision making point i.e. access point. Differentiated Services are helpful for the distributed QoS, since it is implemented in all of the network devices that forwards the data packets.

For the integration of all approaches, translation of EDCA priority classes to Differentiated Services classes is done at the access point (shown in fig. 9) that forwards EDCA classified data into the network. Since the applications generating the data also prioritize data with the DSCP value, the priority translation between EDCA and DiffServ is a forwarding mechanism based on the DSCP value with the u32 filters at the access point's queues. The u32 filters forward the incoming packets to their respective queues based on their source/destination IP addresses or port numbers. From there onward, the DSCP value is used to define the priority of data packets in the network core. Adding the network monitoring applications, which decrease their generation data rate based on destination feedback, helps to maintain the needed QoS. Similarly, when the reception data rate is below the configured network bandwidth, the lower priority application (e.g. video application) increases its frame rate/resolution gradually until better video quality is achieved.

V. Conclusion and Future Work

The simulations and the practical test of data prioritization methods show that the high-prioritized data is successfully received at the destination even under congested network conditions. Data loss due to high traffic at a local access point can be avoided with the EDCA. In the case of a local network, which uses both wired and wireless techniques, Differentiated Services can be utilized at routers to forward the high-prioritized data in front of the low-prioritized data (e.g. video streams against data logs). Thus, a combination of EDCA, DiffServ, and application data generation control using SNMP feedback results in the fulfillment of the QoS requirements for the critical data transfer in vehicular agricultural networks.

As future work, an adaptation of the traffic configuration rules at the end devices with the help of SNMP will be investigated. Combining dynamic traffic configuration rules with the dynamic data generation rate at applications along with the EDCA and DiffServ may yield valuable results. A multi-radio routing prototype integrating mobile networks, WLAN, and other wireless technologies for agricultural vehicles is another part of the future work. A multi-radio setup alongside data prioritization methods can also provide important results for areas where mobile connectivity is sparse.

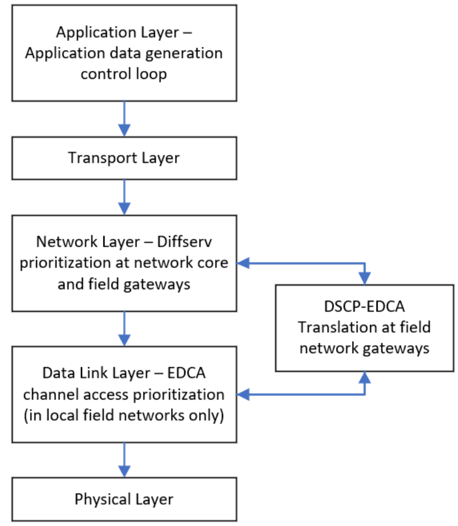

Fig. 9. Network devices architecture.

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