LTE Micro-cell Deployment for High-Density Railway Areas

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Abstract. Long Term Evolution (LTE) is a serious candidate for the future releases of the European Rail Traffic Management System (ERTMS). LTE offers more capacity and supports new communication-based applications and services for railways. Nevertheless, even with this technology, the classical macro-cell radio deployments reach overload, especially in high-density areas, such as major train stations. In this paper, an LTE micro-cell deployment is investigated in high-density railway areas. Copenhagen Main Station is considered as a realistic deployment study case, with a set of relevant railway communication-based applications. The micro-cell deployment is compared with a classical macro-cell deployment in terms of transmission performance. Simulation results show a capacity improvement in the micro-cell deployment and its positive impact on critical (safety) and non-critical applications.

Keywords: LTE, GSM-R, ETCS, ERTMS, railway signaling, mobile communication, network planning, network simulation, OPNET.

1 Introduction

The European Rail Traffic Management System (ERTMS) is a unified train control system, which has become the reference for railway management systems worldwide [1, 2]. ERTMS relies on GSM-R, as a telecommunication technology, to carry the European Train Control System (ETCS) and voice communication between ground and rolling stock.

Today, GSM-R has various shortcomings, especially limited capacity [3, 4]. Several research projects are exploring the replacement of GSM-R by the 3GPP Long Term Evolution (LTE) [5, 6]. LTE is able to support heterogeneous traffic, while ensuring Quality of Service (QoS) differentiation between various applications [7]. Taking this into account, an LTE-based telecommunication network should be able to satisfy current and future needs of railway communication systems. On the other hand, railways are increasingly demanding in terms of radio resources and real-time requirements. In fact, railway operators and infrastructure managers are asking for new communication-based applications [8], in addition to signaling and voice calls. These applications are related to security (e.g. video surveillance, and discrete

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listening), operating support (e.g. platform surveillance, remote maintenance and voice announcements) and entertainment applications (e.g. advertisment broadcasting and Internet for passengers).

Some previous studies point out that LTE may be used in railways for three types of applications [9, 10, 11]:

- Safety-critical applications (i.e. the ETCS railway signaling).
- Applications essential for railway operation (i.e. voice communication).
- Additional applications, which are not necessary for train movement (e.g. video surveillance, voice announcements, discreet listening, file update, Internet for passengers, etc.).

The mentioned studies show that these applications can coexist in a single network, without a negative impact on the performance of safety-critical applications. Moreover, the performance offered to the safety-critical and essential applications is beyond that offered by GSM-R, even in overload conditions [9, 10]. But the same results show that this improvement is limited in high-density areas [11]. This is due to the inadequacy of the macro-cell based radio coverage, which is not able to provide enough resources to all the trains when new application traffic is added. These additional applications are highly demanding in terms of bandwidth. One solution to this lack of resources could be a non-regular radio planning, adapted to the different traffic load in different railway areas.

In this paper, the interest is put on the performance that an LTE micro-cell based radio coverage can offer in high-density railway areas. This should be especially beneficial for the applications consuming a lot of bandwidth. The Copenhagen Main Station is considered as an example of a high-density area. The focus of our study is put on the communication performance (end-to-end delay and packet loss) offered to the ETCS signaling application (safety-critical), the voice call application and video surveillance application. The evolution of these performance parameters is studied in relation to the number of trains, in the considered area. The case study is modeled in a computer-based telecommunication simulator: OPNET Modeler [12].

The paper is organized as follows. Section 2 describes a set of railway applications, their requirements on communication performance and our proposed study case. Section 3 presents the simulation scenarios comparing the alternative radio deployments. Section 4 details simulation results and discussions. Finally, section 5 concludes the paper.

2 Railway Communication-Based Applications and Case Study

2.1 Railway Applications

Today, railway operators and infrastructure managers define several additional applications, along with ETCS signaling and voice communication. In our case study, a set of five typical railway applications is considered, as described below.

1. The European Train Control System (ETCS) is the signaling system defined by ERTMS. ETCS operates on a basis of data message exchanges between On-Board

Units (OBU), which are located in trains, and Radio Block Controllers (RBC), which supervise train movements. ETCS is a safety-critical application and has strict transmission performance requirements. These requirements were defined for circuit-switched based transmission over GSM-R. For packet-switched based communication, as in LTE, there are only tentative requirements available [3]. The average transfer delay of a 128-byte ETCS message is required to be lower than 500 ms. Moreover, 95% of the ETCS messages must be delivered within 1.5 s. The probability of data loss or corruption must be lower than 0.01%.

2. Interphone is the internal railway telephony, essential for railway operation. For instance, it is used for communication between a train driver and the traffic control center. In our case study, each train makes a voice call to the control center every 900 s, on average. Every interphone call generates one uplink stream and one downlink stream, both with a throughput equal to 64 kbps. The call duration is 20 s, on average. The interphone application can tolerate a maximum average delay of 150 ms and a maximum packet loss ratio of 1% [13].

3. Voice announcement informs the on-board passengers about the current traffic situation. Every train receives an announcement from the control center every 900 s, on average. Each announcement has an average duration of 5 s. The announcements generate a 64 kbps uplink stream. The voice announcement application can tolerate a maximum average delay of 150 ms and a maximum packet loss ratio of 1% [13].

4. Video surveillance continuously transmits two real-time video streams from each of the trains to the control center. Video surveillance is based on *Closed Circuit TeleVision (CCTV)* system. Every train carries two CCTV cameras. Each camera generates a constant stream of 62.5 packets (1000 bytes) every second. This application can tolerate a maximum average delay of 100 ms and a maximum packet loss ratio of 0.1%.

5. File update is an application used by the on-board equipment to upload non safety-critical information to the control center. This could be used to upload maintenance data collected by sensors in a train. The application transmits a 7 GB file in the uplink every 20 hours, on average.

2.2 Case Study

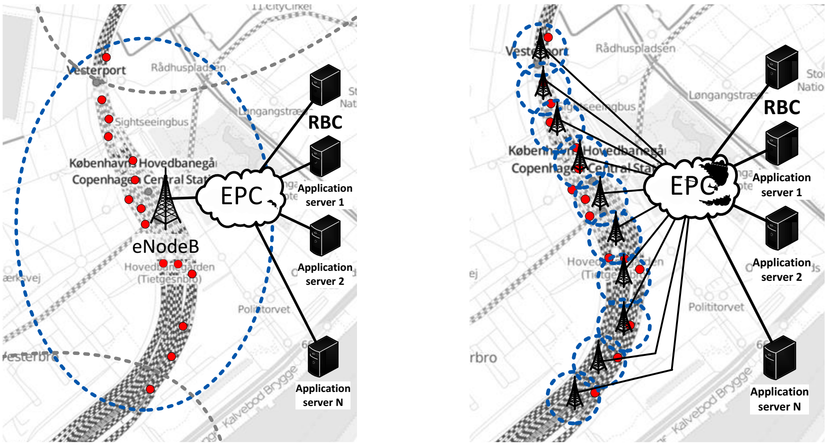
Copenhagen Main Train Station is the biggest train station in Denmark. It has a high train concentration. It is a typical area where a GSM-R network may offer insufficient capacity to serve all the trains [3].

In [10], it was established that up to 27 trains can be expected at Copenhagen Main Train Station in a peak hour. In the future, up to 40 trains are expected.

Two LTE-deployment configurations are considered for this area. Each configuration models one of the two alternative radio network deployments at Copenhagen Main Train Station.

In the first configuration, the macro-cell deployment, an LTE radio network covers the station with just a single radio cell. The cell has a radius of approximately 1 km. This configuration is illustrated in Figure 1a. In the second configuration, the micro-cell deployment, the train station is covered with a set of 10 micro-cells. Each has a radius of approximately 50 m. The micro eNodeBs are placed linearly following the linear shape of the station and the tracks to cover. This configuration setup is illustrated in Figure 1b.

In an LTE radio access network, there is interdependency between cell range, cell-edge throughput and traffic load [14]. Firstly, the smaller the cell range, the higher the cell throughput is. Hence, by deploying micro cells with much shorter range, it is expected that the cell throughput will increase. Secondly, the lower the traffic load, the higher the cell throughput is. In the micro-cell deployment, the traffic load is distributed over more cells than in the macro-cell case. Thus, the traffic load per cell is smaller and the throughput increases.



(a) Macro deployment (b) Micro deployment

Fig. 1. The studied LTE deployments. Map source: [15].

3 LTE Deployments and QoS Configuration

3.1 Simulation Scenarios

For performance evaluation, two simulation scenarios were evaluated. Each scenario modeled one of the two LTE deployments presented in section 2.2.

The trains were modeled as LTE User Equipment (UE), which used the LTE network to connect to the application servers. LTE eNodeBs (eNBs) were connected to an Evolved Packet Core (EPC) node, which modeled the whole functionality of an LTE backbone network, i.e. the Serving Gateway (S-GW), the Packet Data Network Gateway (PDN-GW) and the Mobility Management Entity (MME). The EPC provided connectivity to the railway application servers.

The macro-cell scenario modeled an LTE radio network that covered the station with a single radio cell. The cell operated in the frequency band used currently by GSM-R. The micro-cell scenario modeled an LTE radio network that covered the station with 10 cells. Table 1 presents the parameters of both scenarios.

Our initial simulations showed that the inter-cell interference is a crucial issue in this study, but in a different manner for each scenario. In the macro-cell scenario, the inter-cell interference was modeled by four jammer nodes, deployed at the edge of the studied cell. These nodes simulated the wireless transmissions in the cells surrounding the studied LTE cell.

In the micro-cell scenario, some coordination mechanisms for inter-cell interference avoidance had to be used. For instance, eNodeBs could implement partial frequency reuse [17]. Thanks to this mechanism neighboring LTE cells do not use the same frequencies at cell edges. However, the LTE model in OPNET does not support the partial frequency reuse mechanism. Hence, some additional configuration changes were necessary, in order to make the simulations model as close as possible to real deployments. The effect of partial frequency reuse mechanism was therefore reproduced by a second frequency band of 5 MHz. Every other micro eNodeB used this second band, i.e. two direct neighbor cells operated always in different frequencies. In this way the system performance resembled a system with partial frequency reuse.

Table 1. Simulation scenario parameters

Parameter:	**Macro cell scenario**	**Micro cell scenario**
Frequency band	920 MHz (5 MHz bw.)	5.9 GHz (5 MHz bw.)
eNB Transmission power	36 dBm	1.5 dBm
eNB antenna height	50 meters	10 meters
eNB antenna gain	15 dBi	
UE antenna gain	1 dBi	
Pathloss model	UMa[1]	UMi[2]
Multipath channel model	ITU Pedestrian A[3]	

1: ITU-R M2135 Urban Macro (UMa) [16]. The simulation randomly chooses between Line-of-Sight and Non-Line-of-Sight cases
2: ITU-R M2135 Urban Micro (UMi) [16]
3: The ITU Pedestrian A multipath channel model is chosen because the trains (UEs) in the simulations are considered stationary.

3.2 Quality-of-Service (QoS) Configuration

LTE technology offers a QoS management mechanism based on the *Evolved Packet System (EPS) bearers,* which are used to carry packets with common QoS requirements [7]. Each bearer receives a specific QoS treatment in the radio access, as well as in the core network. Each bearer has a QoS Class Identifier (QCI) associated. This QCI defines a set of node specific parameters (e.g. scheduling weights, admission thresholds, packet discard timer, etc.) that determines the packet forwarding behavior [17].

A railway communication system carries a heterogeneous set of applications. Each has different requirement, as described in section 2.1. Thus, an LTE deployment for railways must use the LTE QoS mechanisms to serve the different applications.

In this work, a QoS configuration for LTE deployments was defined, based on the application requirements presented in section 2.1. Two dedicated bearers were assigned for each of the UEs: one for the ETCS application and one for both voice applications (interphone and voice announcements). The remaining traffic was carried using the best-effort bearer, established for each UE by default. Following the recommendations of Khayat, et. al. in [10], traffic from the ETCS application was carried by a Guaranteed Bit Rate (GBR) EPS bearer. This ensures that safety-critical traffic (ETCS) receives sufficient bitrate regardless of other traffic in the network. More details of the EPS bearer configuration are shown in Table 2.

Table 2. EPS bearer configuration used in the simulations

EPS bearer:	**Safety-critical bearer**	**Medium priority bearer**	**Default bearer**
Application(s)	ETCS	Interphone and voice announc.	Other
QoS Class Identifier (QCI)	3 (GBR)	2 (GBR)	9 (Non-GBR)
Guaranteed bitrate (uplink)	16 kbps	64 kbps	-
Guaranteed bitrate (downlink)	16 kbps	64 kbps	-
Allocation retention priority	1	5	9
Scheduling priority[1]	3	4	9
Delay budget[1]	50 ms	150 ms	300 ms
Packet error loss rate[1,2]	10^{-3}	10^{-3}	10^{-6}

1: Values of these parameters are defined in a 3GPP standard [18]. Moreover, these values are only performance targets and are not strict requirements.
2: Maximum error loss rate in a non-congested network.

4 Simulation Results and Discussion

For the simulation study, we use the OPNET Modeler v. 17.5. OPNET Modeler is a powerful event-driven simulation tool, offering end-to-end simulation capabilities via a rich technology and protocol library. It includes a complete LTE model with all essential LTE features and network equipment.

The simulation scenarios were analyzed in 10 subcases, with an increasing number of trains (UEs) at the station. The investigated range was from 5 to 50 UEs (1 UE per train). Thus, the analysis went beyond the maximum number of trains expected at Copenhagen Main Train Station (up to 40 trains in year 2030 [10]). Every subcase was executed 15 times, with varying random seed numbers. Each simulation run lasted 20 minutes.

In the following, four sets of results are presented. The first is related to the total throughput of the network. The following three are related to each of the considered application categories (safety-critical, essential for railway operation and additional applications).

4.1 LTE Radio Throughput

Initially, the two LTE-deployment configurations, micro-cell and macro-cell, are compared in terms of the radio link throughput. Figure 2 shows the average LTE radio throughput, in the uplink and in the downlink, in relation to the number of trains at the station.

Since the video transmission application sent data in the uplink, the uplink direction carried more traffic than the downlink, as shown in Figures 2a and 2b. Thus, the uplink results are considered to highlight the difference between the two deployments.

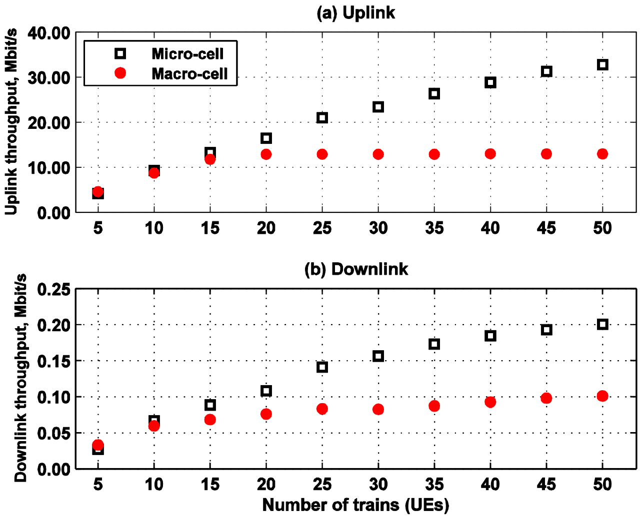


Fig. 2. Throughput in the uplink and the downlink in relation to the number of trains (UEs) at the station for the micro-cell and the macro-cell LTE deployments

In the macro-cell deployment, the average uplink throughput was increasing until the number of trains at the station reached 20. Afterwards, the throughput remained approximately constant at 12.90 Mbps, even with more trains (UEs). Here, the maximum capacity of the macro cell radio uplink was reached.

In the micro-cell deployment, the average uplink throughput increased continuously in the whole investigated range. With 50 trains at the station, the uplink throughput in the micro deployment reached 32.77 Mbps. This higher throughput, compared to the macro-cell deployment, was a result of the additional LTE cells present in the micro-cell scenario. This meant that the traffic load was spread between more cells. As a result, each of the micro-cells was utilized less than the macro-cell. Thus, the micro-cells did not reach saturation. Therefore, the micro-cell deployment offers significantly more capacity than the macro-cell deployment.

4.2 ETCS Safety-Critical Application

This subsection is focused on the communication performance experienced by the safety-critical ETCS application, when other types of traffic are simultaneously present in the network.

The first performance indicator is the mean packet transfer delay in relation to the number of trains (UEs) at the station, as shown in Figure 3a. In the macro-cell deployment, the delay increased rapidly between the subcase with 5 trains and the subcase with 20 trains. Then, the delay stabilized at, approximately, 40 ms. It should be noted, that the radio link utilization also reached saturation in the case with 20 trains. The delay did not increase further thanks to the QoS mechanism. The QoS mechanisms succeeded in keeping the mean delay within the delay budget of 50 ms targeted for ETCS (cf. Table 1).

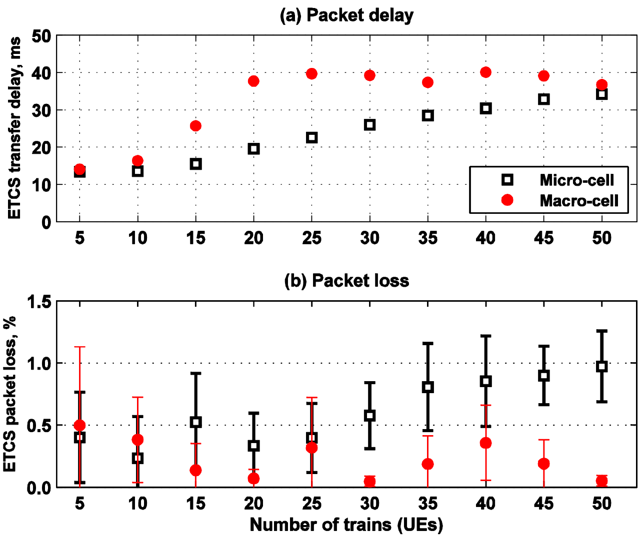


Fig. 3. Mean ETCS packet transfer delay and mean packet loss rate (with 95% confidence intervals) in relation to the number of trains

The micro-cell deployment offered a noticeably lower delay. This is because, the capacity of the micro-cells did not reach saturation. The LTE network provided transmission resources to ETCS, without the need of pre-empting other traffic. This pre-emption would increase delay. However, despite this delay performance difference, both deployments fulfilled the ETCS requirements with a large margin. The recorded values were an order of magnitude smaller than the maximum acceptable mean delay of 500 ms [3].

The second performance indicator is the packet loss rate in relation to the number of trains. According to ETCS requirements, the probability of data loss rate should not exceed 0.01% [3]. Since our ETCS model in OPNET did not include any retransmission mechanism, the data loss rate, at the application level, was equal to the packet loss at the connection level. As shown in Figure 3b, in both deployments, the packet loss rate was larger than 0.01% (between 0.04% and 1.0%).

Therefore, the packet loss rate exceeded the budget defined for this application in the QoS configuration (cf. Table 2). This is due to the inter-cell interference, which increased error rate at the radio link. This interference was higher in the micro-cell deployments. This point is discussed in more details in section 4.4.

Despite these results, which did not meet the packet loss requirements for the safety-critical application, LTE should remain a valid option for railway communication network. Indeed, ETCS tolerates packet delay up to 500 ms. Given that the measured delays are below 50 ms (cf. Fig. 3b), it is possible to retransmit a lost message, even multiple times, without reaching the delay boundary. Therefore, by implementing a retransmission mechanism, at the transport layer or at the application, the data loss rate would improve significantly and stay within ETCS requirements.

Finally, it should be also noted, that the packet loss simulation results did not reach stable values. This high variability between different executions of the same scenario may be due to the random positions of trains in the cells. Our current work concentrates on improving these results by considering fixed positions of the trains in relation to cell edges. This would reduce the variability between different executions of the same scenario.

4.3 Voice Applications (Interphone, voice announcements)

The focus in this section is put on the performance results of the voice applications (interphone and voice announcements), in relation to the number of trains at the station. Both voice applications are carried using a medium priority bearer with QCI 2 (cf. Table 2).

The recorded mean packet delay for voice applications is shown in Figure 4a. In the macro-cell deployment, the delay was between 104 ms (5 trains) and 106 ms (50 trains). In the micro-cell deployment, the delay was slightly larger: between 106 ms (5 trains) and 109 ms (50 trains). For both deployments, the delays were below the delay boundary of 150 ms required by voice applications.

The packet loss rate, in relation to the number of trains at the station, is shown in Figure 4b. In the macro-cell deployment, the packet loss rate was around 1%. It is approximately equal to the maximum packet loss required by voice applications. In the micro-cell deployment, the more trains were present at the station, the higher the packet loss was. In the case with only 5 trains at the station the packet loss was 0.14%. It increased to 1.49% with 50 trains. Thus, the packet loss in the micro-cell deployment fulfilled the requirement, only in the cases with less than 30 trains at the station. Similarly as for ETCS, the packet loss values did not converge yet to stable values.

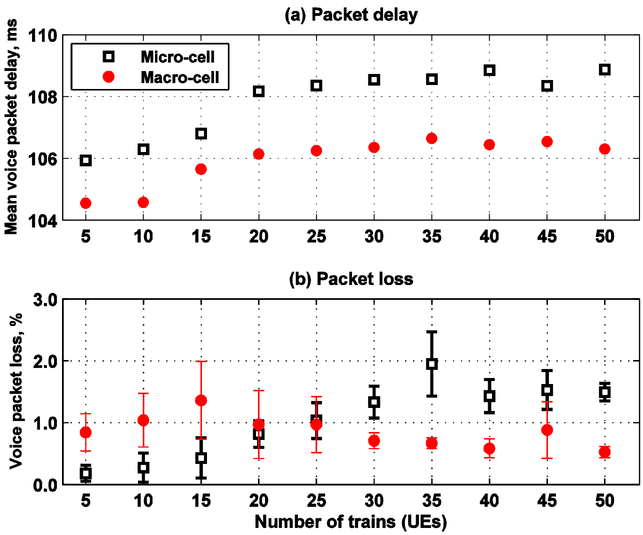


Fig. 4. Mean packet delay and packet loss ratio (with 95% confidence intervals) for voice applications in relation to the number of trains

This slightly worse performance of the micro-cell deployment was a result of the dense cell deployment. As a consequence, many trains (UEs) happened to be located at or close to an edge between two cells. The probability of packet transmission failure at a cell edge was larger than in the area close to an eNodeB. This is because, the bigger the distance to eNodeB is, the higher the interference from the neighboring cells is. As a consequence, SINR decreases and the error probability increases.

4.4 Video Surveillance Application

This subsection is focused on the communication performances experienced by the video surveillance application, which is classified as a best-effort application with QCI 9 (cf. Table 2).

In the macro-cell deployment, the video packet delay grew rapidly as shown in Figure 5a. With 15 trains, the mean delay was 180 ms. Thus, it exceeded the maximum delay required by the application, which is 100 ms (cf. Table 2). In the micro-cell deployment, the packet delay grew significantly slower. This was a result of the higher throuhput offered by the micro-cell deployment. It meant that video packets were not delayed while waiting for available tranmission resources. The packet delay exceeded the maximum allowed only in the cases with 30 trains.

In both deployments, the video packet loss grew with the number of trains in the area, as illustrated in Figure 5b. The maximum packet loss of 1% allowed by the requirements was exceeded in almost all the cases.

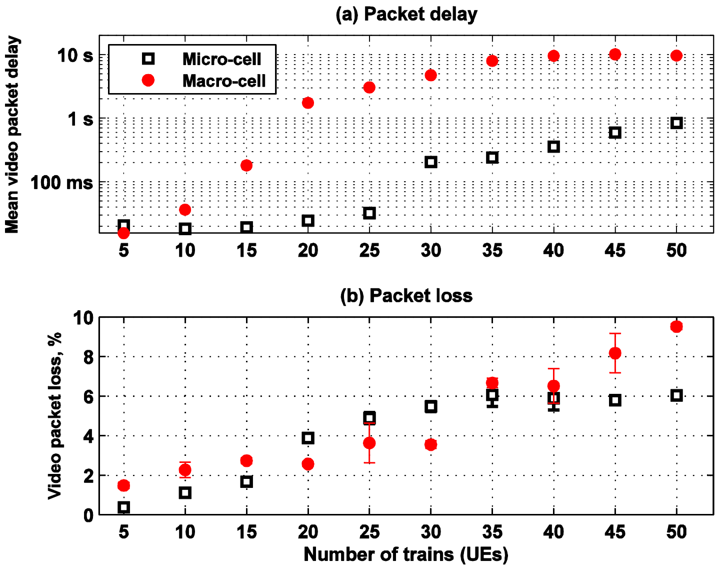


Fig. 5. Traffic throughput, mean packet delay and packet loss rate (with 95% confidence intervals) in relation to the number of trains (UEs) at the station for video surveillance application

4.5 Discussion of the Results

Let us now look, globally, at the performance offered by the two deployments.

Regarding the performance offered to the safety-critical ETCS application, both deployments offer delay performance significantly better than required by railways. However, neither of the deployments respects the packet loss ratio boundary.

For the considered voice applications, both deployments fulfill the delay and the packet loss until a load of 25 trains. The proposed micro-cell deployment is not able to ensure acceptable packet loss performance for voice in cases with more than 25 trains.

For the video surveillance application, the proposed micro-cell deployment fulfills the delay requirement until a load of 25 trains, whereas the macro-cell deployment does it only for no more than 10 trains. Regarding video packet loss ratio, both deployments violate the required boundary.

The micro-cell deployment offers significantly higher throughput, which improves the performance of the bandwidth-demanding application: the video surveillance. However, the capacity increase does not solve the issue of packet loss. In some cases (mainly for voice applications), the micro-cell deployment even increased the packet-loss ratio. This is because of the inter-cell interference, which increases error rate probability at the radio link. In the micro-cell deployment UEs have higher probability of being at a cell edge, where the interference is most severe.

Further Improvements. Additional solutions are required in order to take advantage of a micro-cell deployment without suffering from the mentioned packet loss problem discussed in the previous section. These solutions, which are to address the packet loss threshold violation, are for instance:

- Transport layer, end-to-end, retransmission mechanism for ETCS (cf. section 4.2).
- Reconfiguration of the LTE radio link retransmission mechanisms. LTE includes two retransmission mechanisms: *Hybrid Automatic Repeat reQuest (HARQ)* at the *Medium Access Control (MAC)* layer and *Automatic Repeat reQuest (ARQ)* at the *Radio Link Layer (RLC)* [16]. The packet loss performance of LTE depends on these mechanisms. For example, by increasing the maximum number of retransmissions it is possible to lower the packet loss (at the expense of increasing the packet delay). Moreover, ARQ at RLC can differentiate between EPS bearers. Thus, applications with specific packet loss requirements can be carried in an acknowledged mode to reduce the packet loss, while other less sensitive applications can be carried in an unacknowledged mode. All in all, by configuring HARQ and ARQ properly the packet loss can be reduced.
- Reconfiguration of the LTE link adaptation mechanism, which chooses the radio modulation and coding scheme depending on the observed *Bit Error Ratio (BER).* The target for the link adaptation mechanism is to receive 90% of the transmitted packets correctly in the first transmission attempt. This results in high utilization of the radio link and a high overall throughput [7]. However, in a railway LTE network, robustness is more important than capacity due to safety concerns. Thus the link adaptation target should be increased, e.g. to receive 95% or 99% of packets correctly in the first attempt. This can be done by choosing more robust modulation and coding schemes. This would reduce the packet error probability, at the expense of reducing radio capacity. It should be also considered whether the LTE network could not take into account QoS requirements of an application, when choosing the modulation scheme.
- Adaptive video coding for video surveillance, which could reduce its data rate when the video transmission performance drops.
- Reduction of the number of simultaneous video streams transmitted in the network. By lowering the offered traffic it should be possible to avoid congestion and reduce the inter-cell interference.

5 Conclusions

LTE may become an element of future railway communication networks. This may solve railway communication-related problems and open the way for new possibilities. LTE supports new railway applications, such as video surveillance and file update. However, these new applications are very demanding in terms of throughput. Thus, railway radio access networks must be redesigned, especially in high-density railway areas, e.g. major train stations.

In this paper, an LTE micro-cell based deployment for Copenhagen Main Train Station has been presented and compared to a macro-cell based deployment. Simulation results have shown the capacity improvements of the micro-cell deployment and its positive impact on ETCS transfer delay. Moreover, a significant improvement in video throughput and video packet delay has been observed. Nevertheless, further work is required, since micro-cell deployments increase inter-cell interference. As a consequence, the packet loss increases above the values acceptable for railways. Thus, the significant packet loss becomes the greatest challenge for LTE as a likely railway communication technology.

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