Communications based train control with Ad-hoc networks

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Abstract – Metro intelligent transport city systems should ensure a high train cadence and have increased safety in high traffic conditions. Current signaling systems CBTC can provide a safe minimum distance between two successive trains - 50 m theoretically but practically 200 m due to delays in the transmission chain of processing and transmission of data, which includes the central server, interlocking equipments by local stations and adjacent systems. The new system aims to reduce the gap by using direct communication between successive trains so as to eliminate delays due to communication equipment exclusively at reserve and subsequently lock the route.

Keywords- intelligent Systems, dynamic networks, ComputerBased Train Control system, ad-hoc networks.

I. INTRODUCTION

Similar to the surface rail system, the metro train system is based on safety signaling, this is giving the driving conditions to the driver. Technical attributes of this signaling system are the key factor that determine the number of trains that can run on a line within an hour [1].

Blocks and lateral fixed indication signals are included in a standard railway signaling system. Which signaling system theoretically allows the subway trains to travel at a headway interval of two minutes, depending on the length of fixed blocks. The transport capacity at its best 80% of maximum capacity corresponds to a total of 24 trains per hour.

Moving block signaling is a modern signaling system which obviously increases the transport capacity. Moving block can be compared with the movement of vehicles on the highway where the entire column go at the same speed and keep a minimum distance between vehicles safety, as like the vehicles are connected between them with a fixed connection. The system monitors the distance between trains and send telegrams to the trains. Telegrams sent to the train are used for automatic train protection systems. With this type of signaling it is possible to achieve a transport capacity of 30 trains per hour, meaning two minutes headway.

This signaling system is known in the literature as moving block CBTC (Communications Based Train Control) system. CBTC system is based on continuous control of the train using the communication between electronic interlocking and on-board systems of the train [2].

The interval between trains is limited due to the delays in communication between train and local or central fixed signaling equipment and the localization errors of the train.

In this paper it is proposed to reduce the metro headway at few meters by using the cooperative networks between smart trains. This new technology can improve and limit the errors which are restricting the headway.

This work proposes the new system and its functional description. Also, the existing communication protocols is analyzed at this time for cooperative networks if these are suitable for our system.

II. PROPOSAL CBTC WITH AD-HOC NETWORKS

The headway is given practical by the time required for the communication between train and fixed equipment, and necessary time to analyze the information received by the interlocking and the on-board computer of the train [3].

Fig. 1 shows the principle of communication of the mobile block CBTC system [4]. During the travel a two trains at 80 km per hour the time necessary for communication and data processing is compound by the communication time between train 1 and CTC (Central Traffic Control), the time required for CTC computer to process this data and the time for transmission of orders to train 2 for any incident occurred in this period with train number 1, the system needs to modify the order for the train number 2. For this reason the system requires a minimum safe distance, that two trains can be close each other at the maximum distance between them of 200 m. This
distance corresponds to the average metro length of a sector of fixed block [1].

To decrease the distance between two trains [5] in safety condition it is proposed to use a new type of CBTC, with ad-hoc network. This new system uses the communication system of CBTC with the two trains, but also, uses the communication between trains by means of ad hoc networks as in Fig. 2:

![Diagram of CTC and trains]  
**Fig. 2. Communications between CBTC and trains by AD-HOC**

It is proposed, for achieving this AD-HOC network, to use the 802.11ac standard [6]. This standard is part of 802.11 families of wireless communication networks, which provide high speed traffic on local networks in the 5 GHz band.

To improve communication networks the new wireless standard 802.11ac [7] extends the air interface, increases radio frequency bands 160 MHz and uses multiple streams MIMO (Multiple Input Multiple Output) spatial and high density modulation over 256-QAM (Quadrature Amplitude Modulation), unlike 802.11n which uses 64-QAM modulation with rate 5/6. Using “SDMA” (Space Division Multiple Access) technique, initially used in 802.11n, the new standard uses more than 8 spatial beams simultaneously [8].

Due to the risk of wireless network attacks or intrusions [9] there are increased security risks which is affecting the transfer of critical safety messages. These attacks can be prevented by using safety techniques such as those contained in standard EN 50159-2.

III. AUTOMOTIVE AD-HOC NETWORKS ANALYZE

Ad hoc networks have gained attention in the last years because of automotive applications. The scope of this communication system is to avoid the collision between cars, to increase the driver horizon of awareness rely on assumption that the vehicles are able to communicate with each other and with infrastructure. These concepts in general are currently named Vehicular Ad hoc networks (VANET) [10].

IEEE has approved a suite of 802.11p/1609 Wireless Access in Vehicular Environments (WAVE) protocols. In WAVE beacons are broadcasted periodically by each vehicle, where beaconing provides awareness about the vehicles in the vicinity. Communication range is normally in the order of several hundred meters and adopts the distributed medium access control scheme CSMA (Carrier Sense Multiple Access). The channel is divided into the Synchronization Intervals of a fixed length. These intervals have splinted in Control Channel enduring T_{CCH}, Service Channel separated by Guard Times with span Tg, like in fig 3.

Synchronization interval 100ms

![Diagram of CCH and SCH]  
**Fig 3 Temporal relationships in IEEE 802.11p**

Beacons are transmitted during the T_{CCH} and the time is measured using aSlotTime (β). When a node detects an idle channel it starts to decrease one counter every aSlotTime and as soon as the counter turns at zero the node is allowed to access the channel. This process is triggered by the successful transmission event and is AIFS (Arbitrary Inter Frame Space) or in case of an unsuccessful transmission event the time is extended at EIFS (Extended Inter Frame Space).

If there are n vehicles with α contention slots left at the vehicles’ counters and L is the beacon size the number of successful beacon transmissions during the CCH interval of duration t is N,

\[ N(t,\alpha,n) = P_n(\alpha,n) N(t-\beta,\alpha-1,n) + P_1(\alpha,n) \{1+N(t-s,\alpha-1,n-1)\} + \sum_{k=2}^{n} P_k(\alpha,n) N(t-T_{c},\alpha-1,n-k) \]

In according with [9] the target probability of beacon delivery is

\[ P = N(T_{CCH}+T_{g}+L/R,\alpha,n) \]

It uses the notations as follow:

\[ P_i(\alpha,n) = \left(\frac{n}{\alpha}\right) \left(\frac{n-1}{\alpha-1}\right) \]

Where the times are T_{S}=T_{B}+\alpha/L/R + AIFS and T_{C}=T_{B}+L/R +EIFS

Cooperative safety application is based on exchange messages by vehicles. For this messages exchange of it is possible to use the already existing cellular infrastructure. In this case 3GPP LTE protocols is used.

Like in cellular communication there is now time for down-link (DL) and time for up-link (UL) splinted in timeslots. A special sub-frame (fig. 4) includes DwPTS (down link Pilot Timeslot) of duration d, GP (guard period) of duration g and UpTS (up link Pilot Timeslot) of duration u.

![Diagram of LTE temporal frame]  
**Fig 4 Temporal frame in 3GPP LTE**
3GPP LTE protocol transmission is realized using frames. One frame is composed of 10 subframes of length x. Here three sub-frame types are used, these are Special Sub-frame, Uplink Sub-frame or Downlink Sub-frame. The special sub-frame includes DwPTS (downlink plot timeslot) of duration d, GP (guard period) of duration g and UPTS (uplink Pilot Timeslot) of duration u. Seven uplink/downlink configurations are specified, which assign a particular type for each Sub-frame. In accordance with [10] the target probability of beacon delivery is

\[ P = 1 - \left( \frac{\bar{A}(\gamma)N + \bar{B}(\gamma)}{Ncell N} \right) \]

This probability is calculated with the consideration of a sequence of Sub-frames during the beaconing period starting from the first UL sub-frame and ending with the last DL sub-frame. The following recursive relationships are valid for the beaconing:

\[
\begin{align*}
A(1) &= \min (U(1), Ncell), \\
\bar{A}(1) &= \min (U(i), A(i-1)) \\
A(i) &= \bar{A}(i-1) - A(i) \\
B(1) &= \min (D(1), A(1)N), \\
\bar{B}(i) &= \min (D(i), B(i-1) + A(i)N) \\
B(i) &= A(1)N - B(i) \\
\end{align*}
\]

Where \( A(i) \) is the number of vehicles which transmitted in the i-th sequence of UL Sub-frames, \( \bar{A}(i) \) is the number which has not yet transmitted, the same \( B(i) \) and \( \bar{B}(i) \) for sequence downlink. The number of beacons which can be transmitted during the i-th sequence of uplink sub-frames is \( U(i) \) and the analogous for downlink is \( D(i) \)

\[
\begin{align*}
U(i) &= \frac{u + Z_{UL}x}{L/R_U} \\
D(i) &= \frac{Z_{DL}x + d}{L/R_D}
\end{align*}
\]

Notations, \( Z_{UL} \) and \( Z_{DL} \) are the number of sub-frames in the i-th interval for uplink or downlink.

The following conclusion can be drawn from the above probabilities:

- using 802.11p for any vehicle number under 50 the \( P \) never exceeds 0.83 which is lower than required in typical safety applications for any contention window,
- the abilities of LTE to support beaconing for vehicular safety application are poor.

Given the above it can be concluded that the protocols used in vehicular AD-Hoc networks are not suitable for our scope.

IV. CBTC ARCHITECTURE WITH AD-HOC NETWORKS

The CBTC system architecture used today [11] [12] [13] in subways in the entire world is presented in figure 5. The "IL" are the local interlocking which are controlling the field objects:

According to the system structure shown in figure 3, three main groups of functional blocks grouped as follows can be distinguished: fixed equipment located on site, on board equipment and mobile communication systems (track-to-train and track-to-central control) [14].

Track equipments consist of local interlocking and CTC which supervise trains throughout the network and send orders for local interlocking stations. Local systems are designed to provide interlocking of necessary routes for safety train traffic by checking the routes, command and verification of rail objects and transmission of the orders required for train movement.

Local stations receive the telegrams broadcasted by the trains, which provide the identification of the train, the exact position of the train and technical information about general status of the train and the own braking curves depending on train load. With these, the local stations can identify the exact position of the train and ensure the safety conditions for train route, so that the train can move safely.

The fixed wayside equipment "envelopes" the train in a safety zone according to its technical features and move the block along the line depending on location data received from the train.

"Envelope" of the trains with a safety zone is done including the communication times train – fixed equipment – train and computation time required by the central computer and train computer information to process the data.

If these times are eliminated, the "envelope" of the train can be done with a much smaller safe distance.

In figure 6 is shown a block diagram of the proposed new scheme of CBTC with AD-Hoc networks:
In the new system it is proposed that the train computers communicate each other via Wi-Fi, so the two trains can run safely and the fixed interlocking system will manage only one group formatted by the both trains together.

The computer of the first train will receive information regarding the movement authority, calculates its trajectory and braking curves depending on its own technical properties and transmits all this information to the second train by the ad hoc network made (WI-FI) between the two trains. The computer of the second train receives orders and conditions about the first train and calculates its own braking curves based on its own technical characteristics. The second train will also receive conditions from the fixed interlocking and compares them with those received from train one, for verification.

Block diagram of Computers on board is shown in figure 7:

![Block diagram of Computers on board](image)

The on board equipment operation is presented below. Using the switch status ATP, ATO or DEP, the driver chooses how to drive the train in ATO, ATP or DEP system. Information about the technical status of the train are collected by the on board computer and communicated to the driver using a multifunction display (DMI).

ATP and ATO computers manage the information received from both systems and transmit the trip settings to the train at the train management computer for application. The running conditions are also calculated based on train’s technical data received from train specialized computers, which holds vital information (emergency stop, the actual speed of the train, apply the service brake, etc.). The train integrity computer keeps track of the train’s wagons, train doors status and technical condition of the train systems. CCTV system manages video streams exchanged between the two trains to allow drivers to see what is happening in front of the train that is connected.

Wi-Fi computer manages data traffic through the AD-HOC network, and is managing the intrusions. This computer can change the Wi-Fi transmission channel to achieve a safe connection between the two trains.

All on-board computers communicate each other via a specialized internal network so that each computer has instant access at the vital informations spread through the train internal network.

V. CONCLUSIONS AND FUTURE WORKS

CBTC system architecture with ad hoc network allows reducing the safety distance between two successive trains below 50 m, which increases the traffic capacity of the transport system. The management of elements involved in the movement of trains is done directly by trains through direct data transfer between them, no longer involving the fixed interlocking. The local interlocking will take into account both trains like a assembly and will send orders to this assembly.

The system which uses communication via Wi-Fi, being open and showing the risk of attacks and unwanted intrusions that may affect the safety messages, should use special security techniques.

The proposal to use the new 802.11ac standard for Wi-Fi communication brings a level of safety by using the 5 GHz band, which currently is a little used band and can provide high data flow through the network (over 3GB / sec). Also it is possible to use the 802.11p protocols but this is focused on automotive field and for trains is not suitable.

In the future works we will focus on detailing the communication protocol for this particular case.

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