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Tao Wen, Costas Constantinou, Lei Chen, Zhongbei Tian and Clive Roberts

***Abstract*—Communication-Based Train Control (CBTC) systems are a new generation of metro signaling system dependent on wireless technology, which is not compatible with the safety critical requirements of signalling systems. Improved access point (AP) deployment can improve the reliability of wireless CBTC systems. This paper introduces a method for optimal AP deployment. To validate the optimal AP deployment strategy, an integrated simulation environment is used to test the optimized AP deployment.**

***Index Terms*—Communications-based train control system (CBTC), access points , deployment optimization, channel modelling and Data Communication System (DCS).**

I. Introduction

With many major emerging economies experiencing huge economic growth and population expansion, the demand for a safer, more efficient and comfortable public mass transport systems is urgent. Metro systems are a good choice for new mega-cities, as they meet the increasing need for low emissions and high capacity transport [1]. By utilizing modern signaling systems, known as communication based train control (CBTC) systems, instead of traditional railway signaling systems based on track circuits, metro systems can increase capacity and lower the safety risk in operation. Because less infrastructure is required, the cost of building and post-maintenance can be significantly reduced.

As CBTC systems are automatic train signaling systems, they employ high-capacity bi-directional train to ground communication technology to guarantee that the wayside zone control (ZC) centre knows the accurate location and velocity of each running train in real-time; this also allows the running trains to receive movement authorities (MA) continuously [2]. As a main subsystem of the CBTC system, the data communication system (DCS) is responsible for the two-way communication between the train and the ZC via wayside base stations (BS), which are known as access points (AP). A typical DCS is shown in Fig. 1. A number of APs are placed along the track and each of them has a certain coverage. When a train is running in the coverage area of an AP, the bi-directional communication between trains and ground can take place; when a train is leaving the coverage area and is running in another adjacent area, the train to ground communication will be replaced by a new connection.

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Currently, the most popular wireless communication technology used in the DCS is wireless local area networks (WLAN) [3], which is also known as Wi-Fi. In the majority of cases, WLAN-based DCS systems utilize 2.4 GHz industrial, scientific and medical (ISM) band and the IEEE 802.11 family of standards for the media access control (MAC) layer protocol, the working frequency is divided into 14 channels, 5 MHz apart. Due to the limited spectrum, there are overlaps between neighbouring channels, which means that some of the APs may need to partly share the same frequency. As a result, if adjacent APs are too close to each other, serious co-channel interference can happen [1] - [4]. For a DCS, the coverage of APs should be seamless and a proper overlap is necessary to ensure passing trains can carry out a successful hand-over between different AP coverage areas. From the point of view of coverage, a dense deployment of APs is therefore desirable; however, when an AP deployment is too dense this can result in a severe co-channel interference and can dramatically decrease the system reliability of the DCS. To balance the potential risks caused by co-channel interference and the requirement for seamless AP coverage, a well-planned WLAN-based wireless communication system is vital for the operational safety of the CBTC system. The deployment of APs is a very important planning issue because it can not only determine the overall communication performance, but it also significantly affects the cost of the system.

A number of studies have been carried out focusing on the deployment optimization of APs, or base stations (BS). An optimizing arrangement of BS in high-speed railway systems is developed in [5]. More literature focuses on non-railway systems, especially for indoor environments. A placement strategy for indoor code division multiple access (CDMA) wireless communication systems is proposed in [6] to create a practical and useful framework for finding the optimal placement of each BS. However, as this proposed strategy is specifically designed for CDMA systems, most of WLAN systems use orthogonal frequency division multiplexing(OFDM), so the feasibility of this strategy a in WLAN system is required to be further tested. For OFDM-based systems, an optimal AP placement for an indoor OFDM-enabled WLAN simultaneous broadcast system has been proposed in [7], this being a good example which has the potential to be adopted in AP deployment design in metro systems. However, this approach assumes low movement transceivers in an indoor environment, and in CBTC systems, the trains are moving at a relatively high speed, invalidating some of the underlying assumptions made in [7]. In other research, AP placement is considered together with channel assignment in order to achieve a better optimiza-

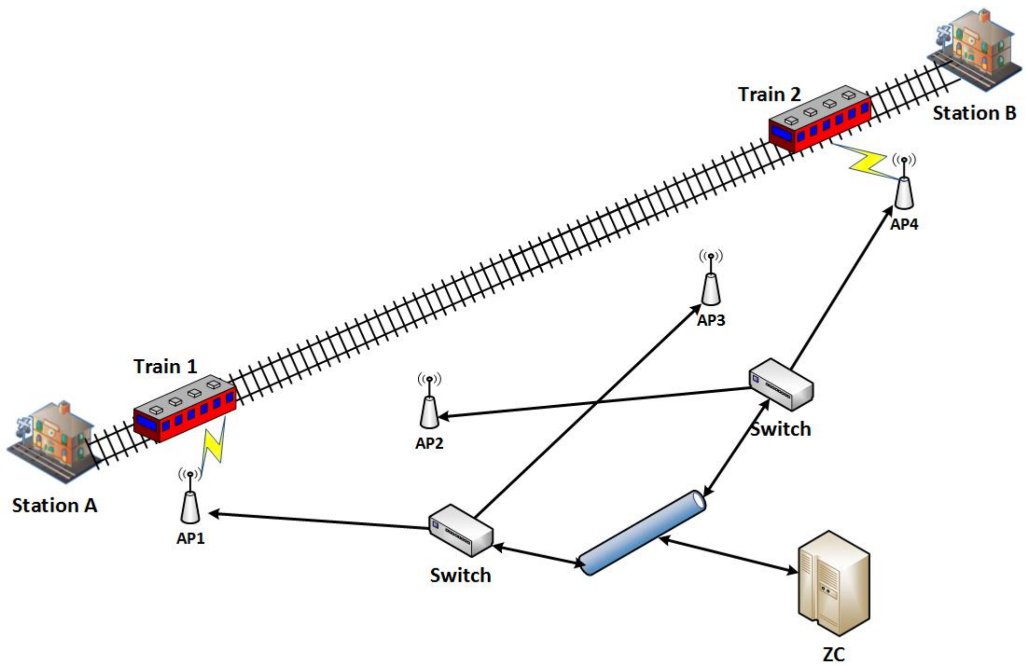


Fig. 1: A diagram of a communication-based train control (CBTC) system

tion result: In [8], a joint and separate optimization planning method for both AP placement and channel assignment in WLAN systems is proposed. In [9] and [10], an optimized AP placement integrated with channel assignment for WLANs is discussed, focusing on indoor environment scenarios. For these proposed strategies which take channel assignment into account, the co-channel interference can be efficiently controlled, and consequently, the communication capacity and quality can be improved; however, as the transceivers are supposed to be static, the applicability of these approaches to CBTC systems is restricted.

Although the question of how to optimize the deployment of APs or BSs has been established in the mobile communications literature, to the best of our knowledge, all of these established AP optimization methods are applicable to non-CBTC system environments and no previous work takes into account the mobility and topographical constrain features of CBTC systems. The most critical problem underlying any AP deployment methodology is how to manage the trade-off between capacity and seamless coverage, both of which are determined by the relative positioning of APs. There are a number of significant uncertainty factors in metro systems, including the tunnel and station environments (e.g. the presence of other trains can alter the propagation environment significantly), time-variable potential co-channel interference sources, etc.. These uncertainties can degrade the system capacity (achievable bit rates) and signal coverage (percentage of space and time where the minimum acceptable bit rate is achieved), which make the optimized AP deployment very difficult to achieve. The main difficulties lie in:

1) Consolidating and expanding the range of radiowave propagation models required to reliably predict signal strengths in a comprehensive range of metro environments;
2) Using suitable metrics to precisely measure the wireless data exchange performance in WLAN of CBTC systems;
3) Integrating the CBCT relevant radiowave propagation models and the system performance metrics to propose the cost function;
4) Implementing the optimized deployment in an integrated simulation environment to quantitatively evaluate the overall CBTC system performance in detail.

This paper is arranged as follows: in section II, a brief overview of wireless communication in CBTC systems is given, and the potential risks are discussed. In section III, the AP deployment optimization problem is formulated, and the relevant cost function is proposed. In section II-E, the outage probability is derived, which is used for measuring the feasibility of AP deployments. Then, in sections IV, a solution method for searching the optimal AP deployment is discussed, and a case study is considered. In section V, the optimization result is validated and discussed. In the final section, the conclusions and future work are drawn.

II. Brief Overview of the DCS in CBTC Systems

Due to the nature of radiowave propagation, there are number of factors which can affect the received wireless signal quality and propagation delay in both underground and overground environments (e.g. area path loss, multipath propagation shadow fading, co- and adjacent channel interference, latency caused by handoff). In this section, a brief overview of wireless communication in the DCS is given, and the factors which can significantly impact the DCS system performance are introduced.

A. Brief Overview of Wireless Communications in DCS

As shown in Figure 1, the DCS system is a decentralized system, which is formed by a ZC, APs and train on-board transceivers. The data connections in DCS systems are achieved in two ways, one is the wireless WLAN used between train and AP; the other is a wired backbone network, used between the AP and ZC. One of the main functions of DCS is to send and receive control data between the trains and the wayside APs continuously through the WLAN [11] - [12]. In DCS, the train status data are transmitted from trains to ground via the APs. The data includes the train identification code, velocity, direction and location. Based on the received data, a moving authority (MA) is generated by the zone controller (ZC) centre and returned back to the train. Without receiving the MA the train will be unable to move beyond the next safe position. The whole railway track is divided into several sections; each section is governed by the ZC. The up-link from the train to ground ensures that the ZC is able to know the status, including speed and location, of each train continuously; the down-link from the ground to the train can deliver the MA to the train in real-time.

The purpose of placing APs along the track is to organize contiguous and seamless radio coverage; under this coverage, continuous data transmission between running trains and the ZC can be achieved. Conventionally, in designing a DCS, the method of determining the deployment of APs mainly relies on the gained engineering experience and prior onsite measurements. After the designed AP deployment is implemented, testings and validation of the network performance is conducted, some changes are adopted to fix the spotted design flaws.

This method is already well-developed and has been widely used in DCS design. However, due to the lack of theoretical underpinnings, and from a long term point of view, the achieved system functional robustness is not guaranteed and crucial concerns for the operating safety of the metro system could potentially be raised. Moreover, a mass deployment of CBTC systems would render the existing methods impractical as they employ highly time-consuming empirically-derived data to realize each deployment.

Due to the technical features of WLANs, when a train is moving around the boundary of adjacent AP coverage, a handoff procedure will be triggered. During the whole journey of a train, handoff can frequently happen, for example, in Hefei Metro Line I in China, the 25 km long track has around 150 APs working in one direction, which means 150 handoffs are received. Because the handoff procedure can make the communication quality rapidly change, handoff procedure is a big threat to the operation safety of CBTC systems. In addition to handoff, there are many other threats to the dependability of the DCS. Propagation path-loss and shadowing effects decrease the power spectrum density of the received signal; co-channel interference between adjacent APs will result in a low signal-to-interference ratio and causae a higher bit error rate (BER). All these factors should be accounted carefully in conducting a deployment optimization.

B. Handoff Procedure and Latency

A typical handoff procedure model followed by the majority of WLAN-enabled systems [35] is shown in Figure 2. To ensure the WLAN-enabled systems have high reliability, in IEEE 802.11 protocols, carrier-sense multiple access with collision avoidance (CSMA/CA) is widely used in the media access control (MAC) layer. The CSMA/CA method uses interframe space (IFS) and contention window (CW), which is based on a binary exponential back-off timer, to control the media access. For setting different priorities, different types of IFS are entered prior to the transmitted packet, and if the transmission is failed and a re-transmit is triggered, a back-off timer will be entered prior to attempting to re-transmit. The back-off timer is randomly chosen from 0 to the minimum CW size, and if the re-transmissions continue to fail, the CW size will be exponentially increased until it reaches a maximum CW size.

Handoff procedures can result in a high packet loss. There are two different types of packet loss, which are caused by packet collisions and errors respectively. However, by taking the metro system environment into account, packet collisions only rarely happen, so the errors will mainly arise from the main packet loss. Due to the mechanism of WLAN-enabled systems, when a transmitter does not received an acknowledgement (ACK) within a timeout interval, the packet will be assumed as loss and re-transmission will be triggered.

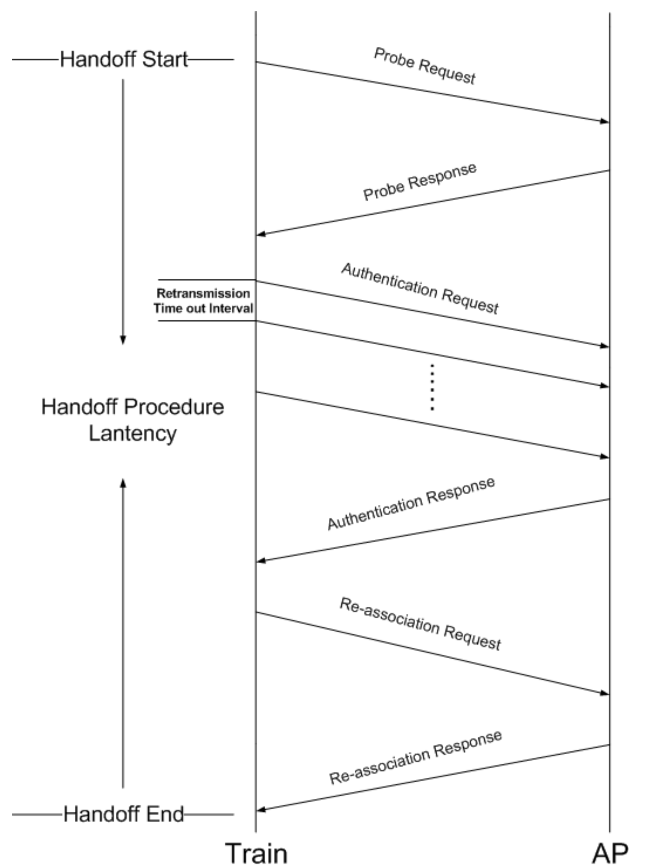


Fig. 2: A Typical IEEE 802.11 Handoff Procedure

After n re-transmissions, the MAC layer delay T_{MAC} in a

802.11 WLAN-enabled system can be expressed as [16]

$$\begin{aligned} T_{MAC}(n) = T_{DIFS} + T_{data} + T_{SIFS} + T_{ack} + T_{DIFS} \\ + T_{backoff}(0) + T_{DIFS} + T_{data} + T_{SIFS} + T_{ack} + T_{DIFS} \\ + T_{backoff}(1) + ... + T_{data} + T_{SIFS} + T_{ack} + T_{DIFS} \\ + T_{backoff}(n-1) + T_{DIFS} + T_{data} + T_{SIFS} + T_{propagation} \end{aligned} \quad (1)$$

where T_{ack} is the required time for generating an ACK frame; T_{SIFS} and T_{DIFS} are the short interframe space (SIFS) and distributed coordination function (DCF) interframe space (DIFS) respectively. These two types of interframe spaces can give different priorities for different transmitted packets; $T_{backoff}(n-1)$ is the backoff time after at n times packet re-transmission happened; $T_{propagation}$ is the propagation time for the transmitted packet from the transmitter to the receiver; T_{data} is the time consumed for generating the transmitted packet, which depends on the the packet length and the data link rate.

Figure 2 shows a typical handoff procedure, which comprises three pairs of packets, i.e., probing, authentication and reassociation. The latency caused in probing process is dominant [35]. It is assumed that each packet has the same chance of being delayed. As a result, the handoff procedure latency $T_{latency}$ after n re-transmissions of a packet can be expressed as

$$T_{latency} = 4 \times T_{MAC}(n) + T_{processing} + T_{probing} \quad (2)$$

where $T_{processing}$ is the hardware response time of a transceiver before starting working, $T_{probing}$ is the latency caused in probing process.

In a DCS system, to guarantee the continuity of the packet transmission, a very strict maximum handoff procedure latency must be applied.

C. Propagation Path-loss and Shadow Fading

To guarantee the train-to-wayside wireless data transmissions ~~is~~ are correct and continuous, the power strength of received signal must be above a certain level all the time. During the signal propagation, the signal strength will be unavoidably attenuated because of path-loss and fading.

Path-loss is the reduction in power of the radiowave as it travels in space. Path-loss has a positive correlation between distance and the degree of attenuation, which means that the longer the signal travels, the more serious the decrease in signal power.

Fading can be caused by many factors. For example, multipath propagation can cause multipath fading, and large obstructions, including hills, ceilings and walls, can cause shadowing fading. Most DCS in CBTC systems use OFDM-based WLAN, a multi-carrier modulation scheme which employs a guard time interval enabling error free operation in multiple path environments with delay spreads roughly less than or equal to the guard interval. This scheme can mitigate the influence caused by multipath fading. So in this paper only shadow fading is accounted for.

The shadowing effect can be seen as a deviation of the path loss which statistically obeys a log-normal distribution with a varied mean value and standard deviation [22] and [14]. This distribution can be expressed as

$$P(x_{dB}) = \frac{1}{\sqrt{2\pi}\sigma_{dB}} \exp[\frac{-(x_{dB} - m_{dB})^2}{2\sigma_{dB}^2}] \quad (3)$$

where σ is the signal strength standard deviation in dB; m_0 is the mean power of the received signal in dB.

By combining the path-loss and shadowing fading together, at the propagation attenuation distance d, the received power P_r in logarithmic units is [23]

$$\begin{aligned} P_r(d)[\mathrm{dB}m] = P_t[\mathrm{dB}m] + G_{tx} + G_{rx} \\ - 10n\log_{10}(\frac{d}{d_0}) + 10\log_{10} K - x_{dB} \end{aligned} \quad (4)$$

where P_t is the transmitted power; G_{tx} and G_{rx} are the transmitting gain and receiving gain respectively; n is the path-loss exponent, which is variable in different propagation environments; K is a dimensionless constant which is the a path-loss gain at a reference distance [24]; d_0 is a reference distance for the far field of an antenna; x_{dB} is the shadowing. Without accounting for x_{dB}, P_r will be the received mean power.

D. Co-Channel Interference within APs

Co-channel interference happens due to APs having the same working channel frequency or the working channels having the partially overlapping frequency channels. As proposed in [15], proper channel assignment can help to mitigate the degree of co-channel interference. However, due to a dense placement of APs, it is very difficult to eliminate this kind of interference, as the reuse radius is limited. The signal-to-noise-and-interference ratio (SNIR) is used as the metric to measure how serious the interference is. The SNIR is expressed as

$$\mathrm{SNIR[dB]} = 10\log_{10}(\frac{E_b}{N_0 + I_0}) + 10\log_{10}(\frac{f_b}{B}) \quad (5)$$

where $\frac{E_b}{N_0+I_0}$ is the energy per bit to noise plus co-channel interference power spectral density ratio; f_b is the channel data rate; B is the channel bandwidth.

In the placement planning of APs, SNIR is a very important variable that should be considered carefully. A too low SNIR can lead to a high BER, which will decrease the reliability of communication in DCS. As a function of $\frac{E_b}{N_0+I_0}$, for binary phase-shift keying (BPSK) or quadrature phase-shift keying (QPSK) modulated system, BER can be expressed as

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}(\sqrt{\frac{E_b}{N_0 + I_0}}) \quad (6)$$

In CBTC systems, since the noise is not the major limiting factor for the SNIR, we use signal-to-interference-ratio (SIR) instead. To avoid the occurrence of a high BER, the strength of co-channel interference must be under a certain level. The most effective way to decrease the co-channel interference level is to increase the channel reuse radius, but it will result in a reduced AP wireless coverage.

E. Outage Probability

Due to shadowing fading, the power density of any signal is randomly attenuated due to propagation in the metro environment, which makes it is impossible to know the exact power of signal at a certain distance deterministically. However, to meet the DCS system requirement of wireless communication, the received power strength of the desired signal exceed the Rx sensitivity, and the SIR must be higher than the protection ratio; otherwise, the performance of the train-to-trackside wireless communication will be below the minimum safety level mandated by DCS, which is called outage. Even though there is no way to predict the exact received signal power, or SIR, we can use a stochastic function to measure the outage probability.

At the receiver, when receiving the desired signal, all of the undesired co-channel signals give rise to interference, but normally just a few of the nearest signals can influence the SIR significantly. In this paper, it is assumed that there are only two dominant interferers which can affect the communication performance significantly; these are generated by the two nearby APs.

As discussed in II-C, when the desired signal and interferences are transmitted through a fading channel and suffer random variation due to obstacles, this is called shadowing fading. The power variability of the desired signal $P(x_0)$, $P(y_1)$ and $P(y_2)$ due to shadowing obeys a log-normal distribution, which can be expressed as

$$P(x_0) = \frac{1}{\sqrt{2\pi}\sigma_0} \exp[\frac{-(x_0 - m_0)^2}{2\sigma_0^2}] \tag{7}$$

$$P(y_1) = \frac{1}{\sqrt{2\pi}\sigma_1} \exp[\frac{-(y_1 - m_1)^2}{2\sigma_1^2}] \tag{8}$$

$$P(y_2) = \frac{1}{\sqrt{2\pi}\sigma_2} \exp[\frac{-(y_2 - m_2)^2}{2\sigma_2^2}] \tag{9}$$

where x_0, y_1 and ~~y_T~~ y_2 are expressed in logarithmic units; σ_0, σ_1 and σ_2 are the deviation in dB of the desired signal and two major interfering signals respectively;m_0, m_1 and m_2 are the received signal mean power of the desired signal and two major interfering signals respectively, which can be calculated by equation (4).

In [21], how to calculate the exact outage probability in presence of two dominant interferers has been proposed. From there we can get

$$P_{out}^2 = P_{out}^1 + P_{add}^2 \tag{10}$$

and

$$P_{out}^1 = P_{out}^0 + P_{add}^1 \tag{11}$$

where P_{out}^2, P_{out}^1 and P_{out}^0 are the exact outage probability in the presences of two, one and zero interferers respectively, P_{add}^2 and P_{add}^1 are the increased magnitude of outage probabilities caused by the extra interference.

To calculate the P_{out}^2, it is necessary to compute P_{out}^1 and P_{add}^1 in advance.

$$P_{out}^1 = 1 - \int_{S_m}^{\infty} P(x) \int_{-\infty}^{x-R} P(y_1) dy_1 dx \tag{12}$$

where P_{out}^1 is the outage probability in the presence of a single interferer, R is the protection ratio in dB, S_m is the minimum required signal power in dBm. Let

$$u = \frac{y_1 - m_1}{\sqrt{2}\sigma_1}, so\ du = \frac{dy_1}{\sqrt{2}\sigma_1} \tag{13}$$

then this gives,

$$\int_{-\infty}^{x-R} P(y_1) dy_1 = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{b} \exp(-u^2) du \tag{14}$$

where

$$b = \frac{x - (m_1 + R)}{\sqrt{2}\sigma_1} \tag{15}$$

So equation (14) can be rewritten as

$$\int_{-\infty}^{x-R} P(y_1) dy_1 = 1 - \frac{1}{2} \operatorname{erfc}[\frac{x - (m_1 + R)}{\sqrt{2}\sigma_1}] \tag{16}$$

Substituting equation (16) into equation (12) gives

$$P_{add}^1 = \frac{1}{2} \int_{S_m}^{\infty} \exp[\frac{-(x - m_0)^2}{2\sigma_0^2}] \operatorname{erfc}[\frac{x - (m_1 - R)}{\sqrt{2}\sigma_1}] dx \tag{17}$$

and P_{out}^0 is the outage probability in the absence of interference given by

$$P_{out}^0 = \frac{1}{2} \operatorname{erfc}[\frac{m_0 - S_m}{\sqrt{2}\sigma_0}] = \frac{1}{2} \operatorname{erfc}[\frac{\alpha}{\sqrt{2}\sigma_0}] \tag{18}$$

where $\alpha = m_0 - S_m$, which is the margin by which the desired signal power exceeds the minimum required signal power.

P_{add}^1 can be simplified by making the following variable transformation:

$$u_1 = \frac{x - m_0}{\sqrt{2}\sigma_0}, so\ du_1 = \frac{dx}{\sqrt{2}\sigma_0} \tag{19}$$

and consequently,

$$P_{add}^1 = \frac{1}{2\sqrt{\pi}} \int_{\frac{-\alpha}{\sqrt{2}\sigma_0}}^{\infty} \exp(-u^2) \operatorname{erfc}[\frac{\sigma_0}{\sigma_1} u + \frac{\tau}{\sqrt{2}\sigma_1}] du \tag{20}$$

where $\tau = m_0 - (m_1 + R)$, and in summary

$$\begin{aligned} P_{out}^1 &= \frac{1}{2} \operatorname{erfc}[\frac{\alpha}{\sqrt{2}\sigma_0}] \\ &+ \frac{1}{2\sqrt{\pi}} \int_{\frac{-\alpha}{\sqrt{2}\sigma_0}}^{\infty} \exp(-u^2) \operatorname{erfc}[\frac{\sigma_0}{\sigma_1} u + \frac{\tau}{\sqrt{2}\sigma_1}] du_1 \end{aligned} \tag{21}$$

A similar derivation for P_{add}^2 yields

$$\begin{aligned} P_{add}^2 = \frac{1}{2\pi} \int_{\frac{S_m - m_0}{\sqrt{2}\sigma_0}}^{\infty} \exp(-v^2) \\ \int_{-\infty}^{\frac{\sigma_0}{\sigma_1} v + \frac{\tau}{\sqrt{2}\sigma_1}} \exp(-u_3^2) \operatorname{erfc}[\frac{z_1}{\sqrt{2}\sigma_2}] du_3 dv \end{aligned} \tag{22}$$

where

$$z_1 = 10 \log_{10}(10^{\frac{\sqrt{2}\sigma_0 v + \tau}{10}} - 10^{\frac{\sqrt{2}\sigma_1 u_3}{10}}) - m_2 + m_1 \tag{23}$$

Defining

$$\tau_1 = m_0 - (m_2 + R) \tag{24}$$

finally yields,

$$z_1 = 10\log_{10}(10^{\frac{\sqrt{2}\sigma_0 v+\tau}{10}} - 10^{\frac{\sqrt{2}\sigma_1 u_3}{10}}) - \tau + \tau_1 \quad (25)$$

In summary, equation (10) becomes,

$$\begin{aligned} P_{out}^2 = &\frac{1}{2}\operatorname{erfc}[\frac{\alpha}{\sqrt{2}\sigma_0}] \\ &+ \frac{1}{2\sqrt{\pi}}\int_{\frac{-\alpha}{\sqrt{2}\sigma_0}}^{\infty} \exp(-u^2)\operatorname{erfc}[\frac{\sigma_0}{\sigma_1}u + \frac{\tau}{\sqrt{2}\sigma_1}]du_1 \\ &+ \frac{1}{2\pi}\int_{\frac{-\alpha}{\sqrt{2}\sigma_0}}^{\infty} \exp(-v^2)\int_{-\infty}^{\frac{\sigma_0}{\sigma_1}v+\frac{\tau}{\sqrt{2}\sigma_1}} \exp(-u_3^2) \\ &\operatorname{erfc}[\frac{z_1}{\sqrt{2}\sigma_2}]du_3 dv \end{aligned} \quad (26)$$

Using equation (26), the outage probability in the presence of two dominant interferences, can be readily calculated. If the outage probability is higher than the certain value, we can assume the wireless connection between the train and the APs is not dependable. The accepted maximum outage probability depends on the specific DCS system requirements, so in planning the deployment of APs, we must carefully specify its value and ensure that during the whole journey along the track the P_{out}^2 remains below the operating safety threshold for the CBTC system for the selected AP deployment.

III. The AP Deployment Optimization Problem

A. Optimization Problem Formulating

Along a track line, there is a continuum of positions where APs can be placed, which makes the AP deployment optimization process very expensive to compute. In this paper, the track is discretized into a finite number of sections; each of the joints between sections can potentially be allocated an AP. As a result, the optimal AP deployment will be a subset of these joints.

When discretizing the track line, a key issue is to find a proper section length, which is a compromise between tractability (long sections) and realism (short sections). When a receiver is moving on the length of track between two APs with the smallest possible spacing, the distance between these two APs ought to be of the order of within a correlation length of shadowing fading, to ensure that a high probability of signal fading is avoided. It has been found that the correlation length range of shadowing is from 5 m in urban to 300 m in rural environments [31]. For a wide arched tunnel environment with dimensions of 9.6 m to 9.8 m in width and 6.1 m to 6.2 m in height, the correlation length is estimated to be in the range of 65 to 100 m [29]. So, in such a tunnel environment, a conservative estimation, will be to set adjacent APs no further than 65 m apart.

In this paper the AP deployment optimization problem is formulated using binary code: For each section joint, if an AP is placed, the corresponding bit will be set as 1; otherwise, the corresponding bit is set as 0. Taking a 6 joints track line as an example, in equation (27), the AP enumeration label is shown in the first row, and the deployment of APs is displayed in the second row. From equation (27) we can learn that there are three APs placed at junctions A, D and F respectively.

$$\begin{pmatrix} A & B & C & D & E & F \\ 1 & 0 & 0 & 1 & 0 & 1 \end{pmatrix} \quad (27)$$

B. Cost Function

In order to perform an AP deployment optimization it is necessary not only to define a cost function, but to employ a notion of adjacency between solutions in the deployment space. To this effect, the binary string representation shown in equation (27) naturally allows the description of adjacency through the metric of Hamming distance [32], [33]. Conveniently, the 2-norm of the binary string is equal to the number of APs deployed, which in the case of equation (27) is 3.

By combining these 6 joints, these AP deployments are divided into 6 groups according to their Hamming distance from the null solution. The grouping result is shown in Table I, and all these 63 AP deployments form a set Θ.

TABLE I: Possible AP Deployment Distribution

Hamming Distance	1	2	3	4	5	6
Number of AP deployments	6	15	20	15	6	1

However, not all of the AP deployments in Θ can be feasibly implemented in the DCS. To measure the feasibility of each AP deployment, the system outage probability is evaluated at every 5 meters. For a feasible AP deployment, at each sampling point, the outage probability of the wireless connection between the train and the associated AP must be lower than a pre-specified threshold,

$$P_{out\_i} \leq R_{outage} \quad (28)$$

where P_{out_i} is the outage probability at sampling point i and R_{outage} is the system outage probability threshold. The calculation of the outage probability and the definition of the threshold are discussed in the sections II-E and IV respectively.

In performing the AP deployment optimization, the optimal deployment is taken to be a global optimum which takes into account the mean and the maximum value of outage probability, the Hamming distance into consideration. A convex cost function (CF) to be employed in AP deployment optimization is defined as,

$$\mathrm{C(N)} = \alpha \times \mathrm{M_{mean}(N)}^2 + \beta \times \mathrm{M_{max}(N)}^2 + \mathrm{HD(N)}^2 \quad (29)$$

where N is an AP deployment. HD is the Hamming distance of N from the null deployment origin; $\mathrm{M_{mean}}$ is the mean value of the outage probability $\times 10^3$, $\mathrm{M_{max}}$ is the max value of the outage probability the mean value of the outage probability $\times 10^2$; α and β are empirically determined system optimization parameters, which can vary for different metro systems.

Consequently, the aim of the optimization will be finding the AP deployment $\tilde{\mathrm{N}}$, which can minimize the cost function, and the problem can be formed as

$$\tilde{\mathrm{N}} = \arg\min_{\mathrm{N}\in\mathrm{S}} \mathrm{C(N)} \quad (30)$$

where S is a parameter space, and the elements of the set S must belong to Θ and satisfy equation (28).

IV. Case Study

In section II-E a stochastic function to calculate the outage probability has been proposed, which can help us calculate the train-to-trackside wireless communication outage probability at a certain point on the track. To validate the outage probability along the whole track, an efficient solution method is required. In this paper, the Brute Force Search algorithm is chosen, which is easy to implement and can guarantee the globally optimal AP deployment can be found. Although the Brute Force Search method does not scale to long tracks or large rail networks, the case study provides valuable insight into the nature of the CBTC DCS optimization problem.

In this section, an indicative case study is carried out: firstly, an assumed track environment is proposed; secondly, a suitable outage probability threshold is determined; then, by using the mathematical formulations proposed in section II-E and the Brute Force Searching method, the performance of all the AP deployments is quantified; finally, by minimizing the cost function proposed in section III, the optimal AP deployment is found.

A. Track Environment

The detailed track geometry is shown in Figure 3. The whole track is divided into 5 sections, which form 6 junctions, namely A, B, C, D, E and F. The first two sections are straight and have equal length of 60 m; the remaining three sections are 20π m long. The whole track is assumed in a tunnel environment and the specification of the tunnel adopts the tunnel dimensions proposed in [29], which is an approximately wide arched tunnel with dimensions from 9.6 m to 9.8 m in width and 6.1 m to 6.2 m in height.

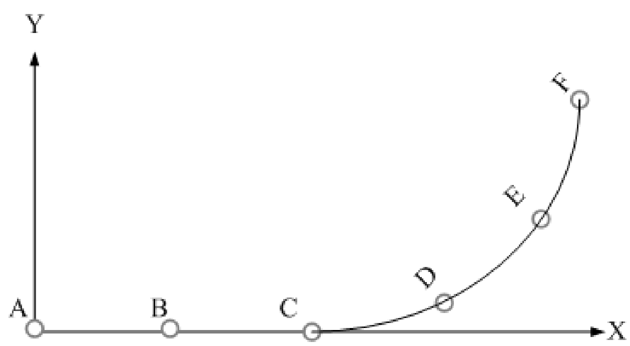


Fig. 3: Track line geometry layout

B. Network Environment and Outage Probability Threshold

Firstly, the key network parameters are defined in Table II. To make these defined parameters more realistic, some of them are informed by measurements in [29]. For the SIR threshold R, this figure highly depends on the BER value. With reference to the Heifei Metro Line One in China, it requires a lower than 10^{-6} BER, and based on equation (6) we can get the energy per bit to noise plus co-channel interference power spectrum density ratio $\frac{E_b}{N_0+I_0}$, which is 3.3612. As the channel bandwidth and data rate have been defined in Table II , by using equation (5), we can get the SIR threshold R, which is -5 dB.

The maximum accepted outage probability is related to the maximum accepted retransmission times during the handoff procedure. For most existing CBTC systems the maximum handoff latency must be shorter than 50 ms [30]. To simplify the problem, it is assumed that there no failure happens in handoff and r retransmissions are triggered to achieve a successful handoff in the presence of data packet losses arising from bit errors. To achieve a conservative handoff latency, we assume that DCS chooses the longest backoff time slot necessary and all the re-transmissions happen in sending the reassociation request frame, which is the longest frame employed during handoff. As the signal propagation time and data generating time are very small, these two delays are considered negligible and ignored, so the handoff latency is given,

$$T_{latency} = 4 \times T_{MAC}(r) + T_{processing} + T_{probing} \leq 50\,\mathrm{ms} \tag{31}$$

where we have

$$\begin{aligned} T_{MAC}(0) = 0.080\,\mathrm{ms};\ T_{MAC}(1) = 0.830\,\mathrm{ms} \\ T_{MAC}(2) = 2.220\,\mathrm{ms};\ T_{MAC}(3) = 4.890\,\mathrm{ms} \\ T_{MAC}(4) = 10.120\,\mathrm{ms};\ T_{MAC}(5) = 20.470\,\mathrm{ms} \\ T_{processing} = 10\,\mathrm{ms};\qquad T_{probing} = 30\,\mathrm{ms} \end{aligned} \tag{32}$$

Combining equations (31) and (32) we get,

$$T_{MAC}(r) \leq 2.5\,\mathrm{ms}, \tag{33}$$

i.e. the maximum latency caused by sending the reassociation request frame is not longer than 3.14 ms. As a result, the maximum retransmission time r should not be bigger than 2. The relevant safety standard [30] requires that the packet loss rate in the train control system must be no bigger than 10^{-3}, giving,

$$R_{outage}^2 \times (1 - R_{outage}) \leq 10^{-3} \tag{34}$$

where R_{outage} is the signal outage probability. Therefore, by calculating this inequality implies that R_{outage} must be less than 3.2%. However, this is just a theoretic deduction, and for a more conservative consideration the maximum acceptable outage probability is set as 2% in this paper.

C. Brute Force Search Result

Using the stochastic function of Section II-E to calculate the outage probability at each sampling point along the track for each AP deployment, the Brute Force Search (BFS) algorithm enables the determination of the optimal AP deployment. The exhaustive searching result is shown in Table III. In this paper, we only consider the AP deployments with a minimum of 3 APs, because too few APs will not be sufficient to account for the impact caused by co-channel interference. Since this case study is sufficiently small to compute exhaustively, this facilitates the empirical determination of suitable, system factors α and β in equation (29) based on engineering experience, which are found to be 17.5 and 2 respectively. A more systematic

TABLE II: Network and Channel Parameter

Frame Name	Max Length	Space Name	Duration	Parameter Name	Value	Chan. Data	Value
Probe Req.	68 Byte	SIFS	10 μs	MAC Protocol	IEEE-802.11	Variance σ_0	2.75 dB
Probe Res.	72 Byte	DIFS	50 μs	Modu. Scheme	OFDM	Variance σ_1	2.75 dB
Auth. Req.	72 Byte	Backoff(1)	31×20 μs	Modu. Type	BPSK	Variance σ_2	2.75 dB
Auth. Res.	42 Byte	Backoff(2)	63×20 μs	Coding Rate	$\frac{1}{2}$	Path-loss Exp.	3
Re-ass. Req.	78 Byte	Backoff(3)	127×20 μs	Data Rate	2 MB/s	Ref. Distance	1 m
Re-ass. Res.	42 Byte	Backoff(4)	255×20 μs	Chan. Ban.	22 MHz		
ACK	14 Byte	Backoff(5)	511×20 μs	Trans. Scheme	CSMA/CA		
		$T_{probing}$	30 ms	Signal Freq.	2.4×10^6 Hz		
		Proce. Time	10 ms	Trans. Power	3.0×10^{-2} W		
		ACK Time	20 μs	Rx Sensitive	-80 dBm		
				Antenna Gain	13 dB		

determination of these two parameters is postponed for a future publication. From these search results, we can arrive at the result that the optimal AP deployment is (011010).

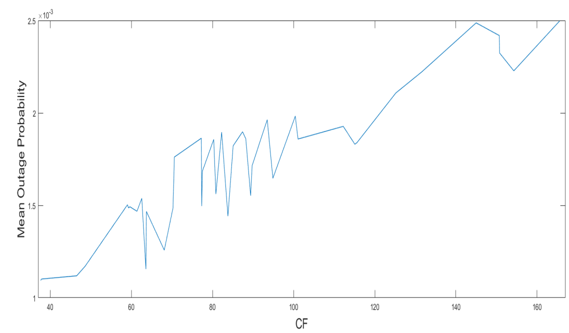
From Figure 4, we can see that as the mean of the outage probability is increasing, the CF is exhibiting a monotonically increasing trend, which demonstrates that the chosen system factors α and β used to calculate CF can discriminate the different performance of each AP deployment.

V. Searching Result Analysis and Validation

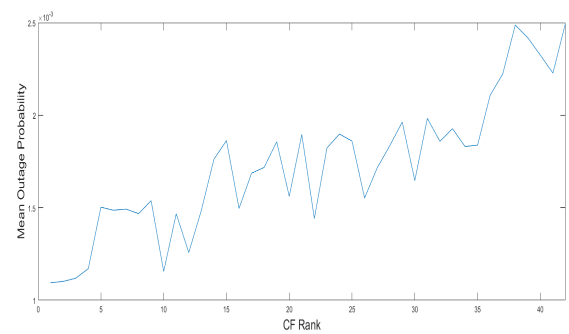
From Table III we can see that there are only 6 results which are compliant with the criterion that the maximum outage probability must be lower than 2%. As a result, it is only necessary to validate these 6 AP deployments.

To prove the optimality, validations are carried out to check the overall DCS performance by using an integrated simulation environment. This simulation environment integrates two separate simulators, BRaVE and OMNet++ [1]; a screenshot of this integrated simulation environment is shown in Figure 5. BRaVE is a microscopic railway simulator, developed by the Birmingham Centre for Railway Research and Education at the University of Birmingham. Railway configuration and traffic, including infrastructure setting, timetabling, route setting interlocking, vehicle type and signaling can be comprehensively simulated using BRaVE. OMNeT++ is a discrete event based simulation environment, which is developed for simulating the channel properties, including signal propagation path-loss, shadowing fading, as well as the operation of protocols corresponding to different network layers, such as the WLAN IEEE 802.11 and Ethernet network IEEE 802.3 protocol. The AP geographical deployment can be implemented in this simulator, and based on this AP distribution and the connection with BRaVE, the DCS performance can be fully evaluated in OMNet++.

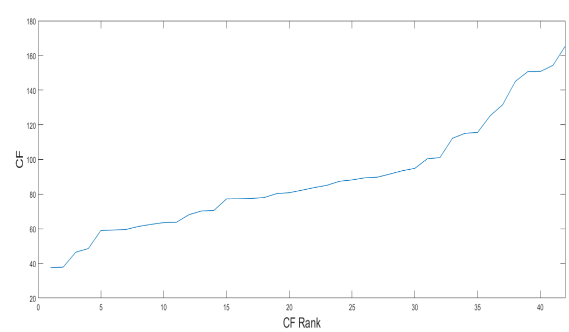
We configure all these 6 AP deployments layout in OMNeT++; meanwhile, the train path is set in BRaVE. When the train is running, all the transmitted data packets will go through the network environment created in OMNeT++. In the validation, we use packet error rate (PER) to measure the overall DCS performance, this is because: 1) PER is a



(a) Mean Outage Probability vs CF



(b) Mean Outage Probability vs CF Rank



(c) CF vs CF Rank

Fig. 4: Searching Result Analysis

TABLE III: Optimization Searching Result

Rank	Deployment	HD	Max ($\times 10^2$)	Mean ($\times 10^3$)	CF	Rank	Deployment	HD	Max ($\times 10^2$)	Mean ($\times 10^3$)	CF
1	011010	3	1.956	1.095	37.621	25	011110	4	3.963	1.442	83.788
2	001011	3	1.956	1.101	37.890	23	101011	4	2.341	1.822	85.078
3	010110	3	2.793	1.119	46.514	24	100011	3	2.781	1.898	87.399
4	110100	3	2.793	1.171	48.608	25	110011	4	2.412	1.860	88.197
5	011001	3	2.290	1.503	59.029	26	001111	4	3.951	1.552	89.387
6	110010	3	2.241	1.486	59.294	27	010111	4	3.339	1.715	89.753
7	010011	3	2.412	1.493	59.621	28	111011	5	1.956	1.835	91.545
8	011011	4	1.956	1.468	61.371	29	100101	3	2.919	1.963	93.480
9	101010	3	2.467	1.538	62.556	30	111100	4	3.963	1.647	94.873
10	001110	3	3.951	1.155	63.577	31	110101	4	2.793	1.983	100.380
11	100110	3	2.920	1.467	63.701	32	110111	5	2.793	1.859	101.067
12	011100	3	3.963	1.258	68.098	33	101110	4	3.951	1.927	112.217
13	110110	4	2.793	1.486	70.256	34	111110	5	3.963	1.831	115.070
14	000111	3	1.910	1.761	70.588	35	011111	5	3.963	1.839	115.576
15	111000	3	1.934	1.863	77.234	36	011101	4	3.963	2.108	125.189
16	101100	3	3.919	1.496	77.320	37	101101	4	3.818	2.226	131.603
17	111010	4	2.421	1.687	77.512	38	111001	4	3.219	2.487	144.977
18	010101	3	2.950	1.718	78.038	39	100111	4	4.021	2.419	150.694
19	101001	3	2.341	1.857	80.287	40	101111	5	3.951	2.324	150.752
20	001101	3	3.818	1.561	80.822	41	111111	6	3.963	2.228	154.263
21	110001	3	2.274	1.896	82.234	42	111101	5	3.963	2.497	165.546

TABLE IV: Validation Result

Deployment	outage:mean ($\times 10^3$)	counts	rcvdPk (%)	PER:sqrsum	PER:stddev	PER:mean (%)
000111	1.761	2791	100	152.39	0.23	6.28(%)
001011	1.101	2872	100	166.58	0.22	5.80(%)
011010	1.095	3039	100	151.46	0.20	4.98(%)
111000	1.863	2929	100	167.24	0.29	6.72(%)
011011	1.468	3838	100	213.83	0.23	6.36(%)
111011	1.835	4642	100	310.12	0.25	7.58(%)

fundamental indicator for measuring the performance of a network. 2) For a certain network configuration, the PER has a positive correlation with the outage probability, which is the key element in the proposed cost function. 3) PER can be easily obtained from OMNeT++, the network simulation. The validation result is shown in Table IV and the PER cumulative density of these 6 AP deployments is shown in Figures 6. From the validation result we can see that the AP deployment of 011010 has a better and more stable performance on PER, lower mean outage probability and the smallest number of deployed APs. As a result, we conclude that 011010 is the optimal AP deployment.

VI. Conclusion and Future Work

A well-planned AP deployment is significant for the CBTC systems, in terms of system reliability and cost. To the best of our knowledge, there is no established method for optimizing the AP deployment in CBTC systems, as none of the existing AP planning methods have been properly and originally designed for a CBTC system featured environment. The characteristics of metro systems, including a typical environment topography and strict requirements on dependability, have not been carefully taken into consideration is established methods, which could lead to an imperfect optimization result. Furthermore, propagation simulators, packet level simulators and train simulators exist, but integrating them together and

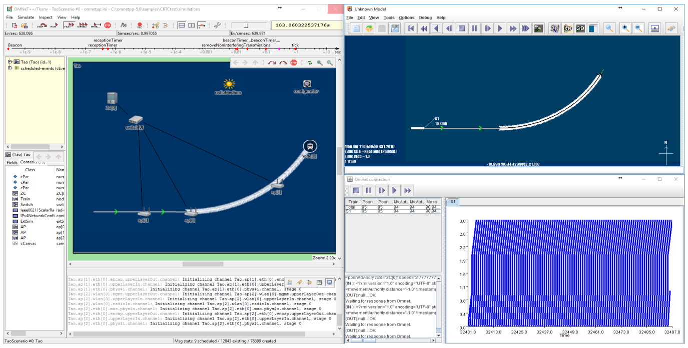


Fig. 5: The Screenshot of the Stimulation Environment

using them as a combined tool to undertake an overall wireless control network optimisation is a new area of study. The main contribution of this paper is to propose an AP deployment optimization method eligible in a railway context and an integrated simulation platform. The originality of this proposed method lies in establishing a totally new research area, which will develop a comprehensive theoretical understanding of factors that can affect the train-to-ground wireless communication quality, and also establish a practical methodology and useful testing tool to help suppliers of CBTC systems improve their ability in designing the AP placement.

In this paper, we have taken path-loss, shadowing effects and co-channel interference into consideration, building an accurate channel model and adapting this to describe the signal propagation and utilize outage probability to measure the wireless connection reliability. To simplify the optimization problem, we discretize the track into equal length sections determined by the shadowing correlation length, and at the edge points of each section, binary integer decision variables are used to formulate the optimization problem. We use a Brute Force Searching method to search each of the AP deployments and obtain their outage probabilities; by integrating Hamming distance, the maximum and mean value of outage probability, we define a cost function, which can be minimized by the optimal AP deployment. The optimization result has been proven in an integrated simulation environment.

However, for a large-scale planning work the efficiency of Brute Force Searching is computationally unfeasible. For instance, if we extend the track to 1.2 km long, under the same optimization configurations and the same optimization procedures, it will require more than 3 years of computation on the existing hardware platform to complete the exhaustive search! Thus, by using the Brute Force Searching method, it is likely to be computationally impossible to optimise an entire metro system, even off-line. In the future, to improve the practicability of our algorithm in the real-world, some further work will be undertaken:

1) Replacing the Brute Force Searching method with a more efficient method;
2) Employing a divide and conquer approach to the complex optimization problem to render it tractable;
3) Determining suitable simplifications leading to approximate optimisation of the CBTC system, compliant with functional constraints;
4) Developing a parametric tunnel propagation model which can be customised for specific scenarios.

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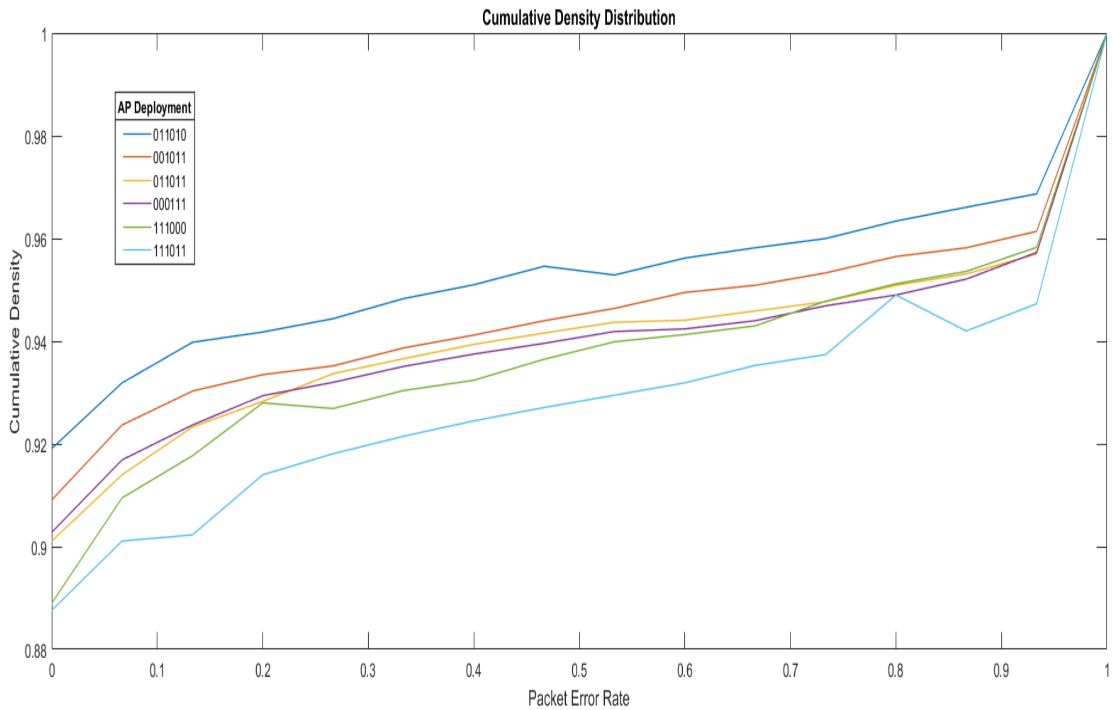

Fig. 6: The Cumulative Density of Packet Error Rate

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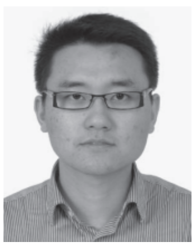

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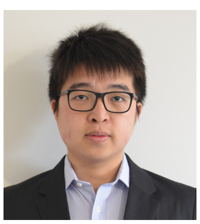

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