Cooperative and Coordinated Mobile Femtocells Technology in 5G High-Speed Vehicular Environments

Mobility and Interference Management

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Abstract- In future wireless networks most the users who will be accessing wireless broadband will be vehicular users. Investigations have already started by the Third Generation Partnership Project (3GPP) to serve those vehicular users cost effectively and improve their signal quality inside vehicles. The deployment technology of Mobile Femtocell (Mobile-Femto) on public transportation is one of the promising solutions to improve the signal quality of those users. Those small cells can reduce or even eliminate the Vehicular Penetration Loss (VPL) impact on the communicated signals. However, Mobile-Femto technology comes with its mobility and interference challenges. Therefore, this work is more concerned with eliminating VPL and interference while improving signal quality and mobility management for train passengers inside High Speed Train (HST) environment. This is because, those HSTs with their well shield carriages are more exposed to Doppler frequency shift, high VPL up to 40dB, low Handover (HO) success rate, high power consumption of UEs and UL/DL interference issues. Thus, initial system level evaluation has shown that the dedicated Mobile-Femto deployment has great potential on improving the vehicular user experience inside public transportation via using Matlab simulator. The Matlab Downlink (DL) results of the proposed interference management scheme showed significant improvement in Mobile-Femto User Equipment (UE) gains (up to 50%) without impacting the performance of macro UEs. In contrast, the proposed Uplink (UL) interference management scheme provides gains for both macro UEs and Mobile-Femto UEs.

Keywords: Interference Management, Intelligent Transportation System, Mobility Management, Small cells technology, Vehicular User Equipment.

I. Introduction

There are always new challenges on future mobile networks with the traffic explosion in today's networks. Previous studies predict that by 2020 the number of connected devices to the internet will exceed 50 billion which in return will require tremendous increase in the networks capacity. Those future mobile networks will enable users to be connected to the internet from anywhere at any time and with anything. In order to achieve that sort of connectivity, it is highly desirable to reduce the environmental impact of mobile communication systems by intelligently deploying new wireless nodes to enhance UEs wireless connectivity. In addition, more studies have predicted that in future wireless networks high number of users who require access wireless broadband will be vehicular. As a result, future vehicles and transportation systems may play an integral role in wireless networks by providing additional communication capabilities and becoming part of the internet communication infrastructure. Thus, Mobile-Femto technology is seen to be a promising solution for the future networks to improve vehicular UEs performance inside public transportation [1]. This study has clearly shown that vehicular UEs are more exposed to high VPL and path loss inside public transportation. Therefore, deploying Mobile-Femto technology inside buses has improved the indoor UEs connection. Fig1 illustrates the Mobile-Femto architecture which has already been investigated in our previous work [2]. The three layers that this architecture relies on are listed below:

1. **The Bus Network Layer (BNL)** consists of the Mobile-Femto and all bus passengers connected to that femtocell.

2. **The Convergence Layer (CL)** aggregates traffic from the Mobile-Femtos in the BNLs via the Backhaul (BH) link and forwards it to the Internet. The evolved eNode Bs (eNBs) enable connectivity for the Mobile-Femto technology.

3. The Access Network Layer (ANL) comprises outdoor wireless LTE and 5G networks that are available along the bus route.

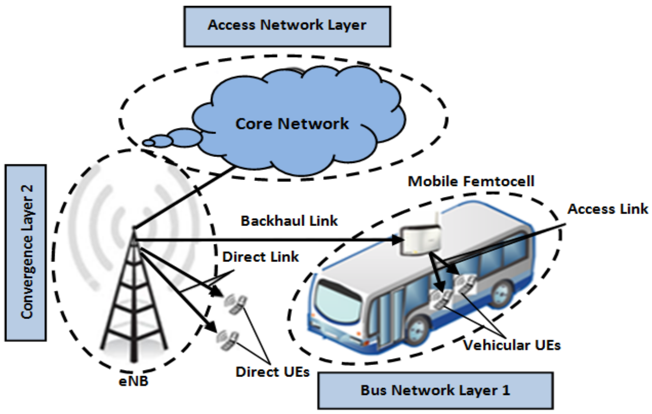

Fig.1.Mobile Femtocell architecture

Nowadays, one of the most used transportation services that saves time and effort are HSTs. HSTs are used all over the world e.g. the TGV Eurostar in Europe and the Shinkansen train in Japan both have similar characteristics and move at 300km/h. Whereas the HST in China has exceeded that speed to reach 350km/h [3]. Those HSTs with their well shield carriages are more exposed to Doppler frequency shift, high VPL up to 40dB, low HO success rate, high power consumption of UEs and UL/DL interference issues [3].

Therefore, the European "Shift2Rail" project [4] has made it clear that there is a persistent need for seamless wireless connectivity, mobility management and high quality of services to be provided for passengers in future rail development. Thus, higher-frequency-band techniques and corresponding mobile communication network should be designed accordingly to provide high capacity and data rate for such future railway services. Although plenty of research has discussed GSM-R networks [5] and 5G networks [6]; however, not many researches dealt with the communications network regarding future railway services. On the other hand, Mobile Communications Enablers for Twenty-twenty (2020) Information Society (METIS) is one of the few projects that are concerned with the possibility of improving the wireless network connectivity by simply using low power small BSs. This project has also introduced the proposal of placing mobile BSs in vehicles, such as cars, trucks, buses and trains to improve vehicular UE performance. In contrast, there are many challenges in deploying these small-cells technology inside moving vehicles, such as BH efficiency, resource allocation, interference and proper mobility management.

Therefore, this paper pays more attention towards improving the performance and signal quality of train passengers after installing small-cells technology inside train carriages. It is also very important to discuss the mobility and interference challenges that accompany the deployment of such small-cells technology.

II. Related Work

The European 5G project (METIS) predicts that by 2020, most of the users who require reliable connection to the internet will be train passengers; where the number is up to 300 UE devices per train [7]. Thus, the E-train projects from the International Union of Railways (UIC) concluded that railway services will spread widely in the next few years and dominate people's lives [8]. In addition, there will be more railway services that are focused on realizing the objective of smart, green, and integrated transport systems [9].

This has created significant motivation to improve the performance of passengers in public transportations, reduce the signal outage and mitigate interference in 5G and future networks. Providing indoor coverage on HSTs with outdoor BSs might not be the best convenient solution due to high penetration losses caused by the Faraday cage characteristics of railcars [10]. This fact has led to poor signal quality inside train carriages where offering broadband services is not always possible [11]. Although, broadband access on trains could be achieved by installing BSs close to the railways; however, this solution is not convenient to train operators due to the high investment needed to deploy such equipment. Besides, such solutions will increase the number of unnecessary HOs; as a result, this has focused the research community on offering solutions that take advantages of the existing wireless infrastructure to propose efficient methods to manage mobility in a seamless way for the end UEs.

Therefore, a cooperative moving Relay Node (RN) system deployed on HSTs has been introduced to enhance the coverage area for HSTs passengers [12]. That study has shown that mobile RNs installed in train environments are capable of overcoming the VPL and providing onboard UEs with quality services. The achieved results via system level simulator showed a slight improvement in the achieved throughput of onboard UEs when compared to direct transmission of those vehicular UEs and outdoor BSs. More work has been done towards improving vehicular UEs signal quality inside high speed public transportation [13]. That study discusses several solutions that have different impacts on future networks. The first common adopted solution for HSTs is to densify the network along the railway to combat high penetration losses. This solution might not be ideal because it cases high numbers of HOs in a very short time. This is due to the increased number of passengers who require HO from one site to another concurrently/ sequentially. Also, such a solution affects system stability and eats up network capacity. On the other hand, a second solution is based on increasing the transmission power of BSs to overcome high VPL. However, this solution causes severe interference between deployed small cells and the served UEs. Added to this, none of those solutions are cost-effective.

In contrast, the authors in [14] have presented a novel HO scheme that utilises Coordinated Multipoint transmission (CoMP) in high-speed Femtocell networks. That study has discussed the deployment of Femtocell technology inside

HSTs to provide passengers with an internet connection. The proposed scheme was aiming for a seamless, deployable and efficient HO procedure for a group of Mobile-Femtos when the train switches between different coverage areas. However, the limitation in that study is the incomplete number of available Physical Resource Blocks (PRBs) in the targeted Macrocells. Thus, most of the Mobile-Femtos connections drop down together with all connected UEs. This occurs when the PRBs in the targeted eNB are fully occupied to the extent that it cannot accommodate any coming Mobile-Femtos. This can easily affect the UEs performance and service satisfaction especially when those passengers feel that they are paying for a service they do not get. Besides that, using Mobile-Femtos high with transmission powers without leaving enough distance between them can cause high interference between the different parties.

Other authors have proposed an efficient HO scheme that contains two procedures to mitigate signal outages of high speed UEs and improve their performance [15]. The first procedure is to accelerate the measurement when the mobile RN knows that the train is moving toward a neighbouring eNB. The second procedure is group HO procedure for all connected mobile RNs that are moving toward known destination.

Thus, it is now obvious that installing small cells inside HSTs to serve train passengers is the future of next-generation networks. Nevertheless, each technology comes with its advantages and disadvantages; e.g. small-cells technology improves the signal quality but it causes interference and mobility issues especially in HST environment. Therefore, this paper pays more attention towards the previous two challenges and provides optimal solutions to improve the signal quality.

III. Mobile Femto Scenario In High Speed Train Environment

Definitely, mobility management is an essential component in mobile cellular communication systems. Mobility offers clear benefits to the end UE i.e. low delay services such as voice and real-time video connections can be maintained in HST environments. Hence, coming up with an effective solution to overcome the above challenges was the main motivation behind proposing the Cooperative and Coordinated Mobile-Femtos (CCMFs) system in HST environments. The CCMFs would be implemented on trains or other large-spatial-dimensions vehicles where those CCMFs are connected to one another through the CrX2 coordination interface as shown in Fig2. This allows high optimisation for the group HO procedure and BH link connection.

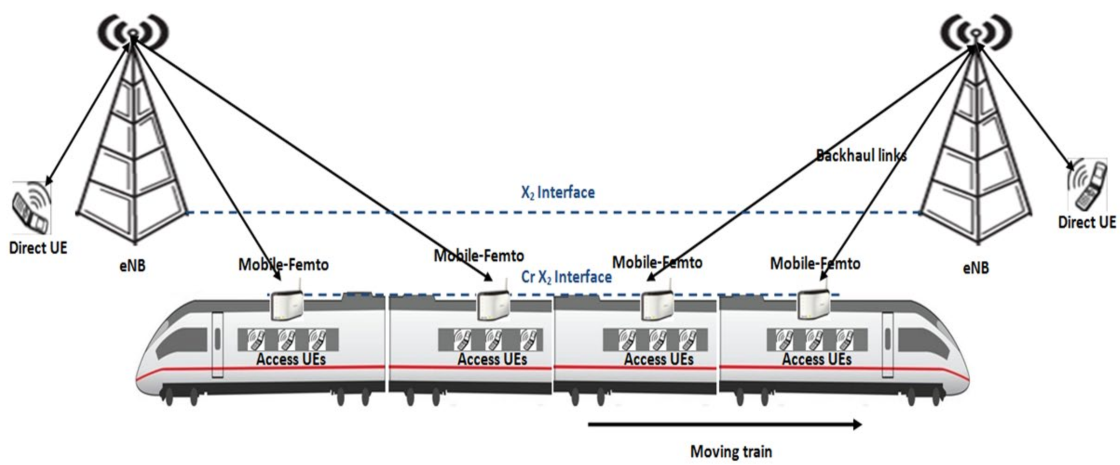

Fig.2.CCMFs scenario in HST environments

However, the limitation in the previous study is the occurrence of interference among RN UEs and Macro UEs since RNs use unlicensed spectrum unlike Femtocells technology in LTE and future networks.

However, one of the main challenges in deploying the CCMF technologies is excessive interference issue caused between the CCMF and the eNBs interference between the different BH links. The following discusses the expected DL and UL interference scenarios of CCMF in HST environments.

A. Downlink Interference Scenario

All possible DL interference scenarios in HST CCMF are illustrated in Fig3.

B. Uplink Interference

On the other hand, all possible UL interference scenarios in HST CCMF are illustrated in Fig4.

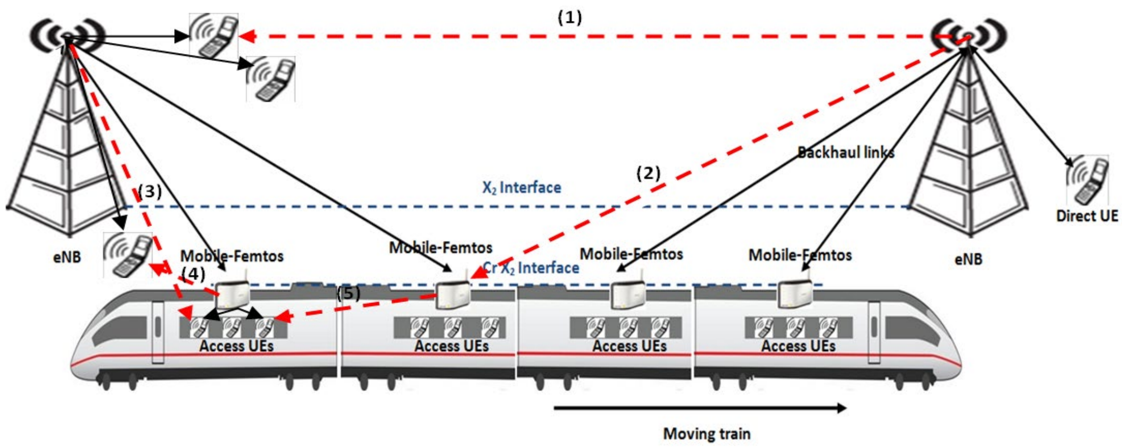

Fig.3.DL interference scenarios

In Case (1) the neighboring eNBs' signals cause interference to macro UEs while in Case (2) the BH links interference occurs when the transmission power of neighbouring eNB is very high that could literally cause interference to Mobile-Femtos served by the neighbouring eNBs.

As in Case (2); the interference in Case (3) is caused by the high transmission power of the eNB which could easily cause severe interference to the Mobile-Femto UEs.

In contrast, Case (4) interference occurs when the Mobile-Femto transmission power is very high to the extent that it could cause interference to the macro UEs within the same network. Finally, the last DL interference of CCMF in the HST environment is represented in Case (5) where interference occurs between the Mobile-Femtos themselves.

The UL Case (1) interference is caused by Macro UEs to other neighbouring eNBs, while Case (2) interference is caused by BH UL transmission of the Mobile-Femto to neighbouring eNBs.

In Case (3) the interference occurs when the Mobile-Femto UE causes interference to the macro UL while in Case (4) the macro UE causes interference to the access link.

As for DL, HST environments, the interference in Case (5) occurs between access links of the many deployed CCMFs within the same network.

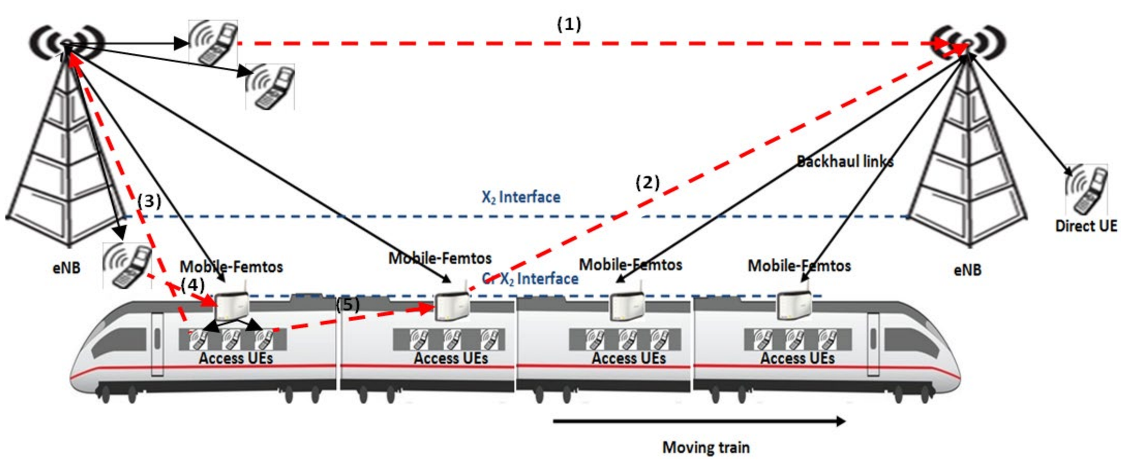

Fig.4.UL interference scenarios

However, interference is not the only challenge in such high speed environments where mobility plays another significant role in this environment. This is because; the forwarding of the data from the source eNB (SeNB) to the target eNB (TeNB) is the main goal of offering seamless HOs in 5G and future networks. Data forwarding typically takes place over X_2 interface between eNBs. In the presence of Mobile-Femto deployments, handing-over the Mobile-Femto itself between Macrocells and forwarding its data is a major challenge in today's networks. This HO procedure takes a place whenever the SINR between the Mobile-Femto and the source eNB gets weaker so the Mobile-Femto in this case initiates a HO procedure to maintain its connectivity with the hosting network. The choice of target eNBs depends on the hosting train path and direction.

It is to be mentioned that the policy of the Call Admission Control (CAC) permits a reduction of the required BW for the coming Mobile-Femto request, which means the system allows a maximum (BW_{eNB} - $BW_{min\text{-}required}$) of BW reduction to handle the Mobile-Femto HO request. Thus, handing over the Mobile-Femto to the target eNB will be accompanied with group UEs HO for all those UEs served by this Mobile-Femto. This HO procedure has been classified into five phases and further explained in our previous work [16]. In contrast, if the $BW_{min\text{-}required}$ is not available at the target eNB even after releasing some of the BW from the existing direct links, the coming Mobile-Femto will not be connected to the target eNB and all its UEs connections will be dropped.

However, the mobility of the installed CCMF in HSTs makes it even more challenging for the cellular operator to control the generated interference of these small cells. Therefore, there are several techniques that could be used by service providers to mitigate the interference between eNBs and CCMF and between the CCMFs themselves in 5G and future networks. These solutions can be summarised into coverage planning optimisation scheme, transmission power controlling scheme and frequency reuse scheme for worst-case interference scenarios when the previous two schemes do not give effective results.

1. Coverage Optimisation

An important challenge for the CCMFs is optimising their radio coverage area dynamically. This has helped in achieving a desired level of performance for mobile transmission, avoiding undesired interference and reducing power consumption. Thus, improving the UE mobile usage experience and reducing the service costs is closely linked to the optimal Femtocell signal coverage as users will feel they are getting the desired services they paid for [17]. In outdoor enterprise environments, several Femtocells might all be deployed together to create joint coverage. This will help in covering large areas, minimising coverage gaps and reducing overlap between multiple Femtocells. Hence, researchers made efforts to optimize Femtocell coverage and reduce the impact of the generated interference as there is a good trade-off between the two on the UEs and network performance [18]. This is because; inappropriate location of the Mobile-Femto installation can create excessive interference between different network parties especially when there is not enough distance to avoid this problem. Besides that, choosing random locations for the Mobile-Femtos may result in coverage holes. That means those Femtocells are placed distant apart from each other where the transmission power is not sufficient enough to reach further users.

Therefore, optimizing the coverage plan procedure is important to have good radio conditions everywhere within the vehicular environment. This can be achieved by mitigating the impact of path loss which in turn can be achieved by installing Mobile-Femtos in appropriate locations with the use of appropriate transmission power. Hence, it is important to note that the used path loss model is Microcell NLOS, which in turn is based on the COST 231 Walfish-Ikegami NLOS model [19]. This model is more convenient to use for urban areas because it takes into account obstruction of building heights and street widths, besides all other factors accompanied with the urban environment. Calculating the Microcell NLOS path loss requires the assumption of some parameters e.g. the antenna height of the eNB is 12.5m, the height of building is 12m, the building to building distance is 50m, the width of the street is 25m, the antenna height of the Mobile Station (MS) is 1.5m, the distance between every two eNBs is less than 1Km and the considered frequency is 1900 MHz [20]. Hence, the NLOS path loss equation can be given by

$$\mathrm{PL(L)} = 34.53 + 38\log_{10}(\mathrm{L}) \qquad \textbf{(1)}$$

Where L is the distance in meters and no less than 20m.
On the other hand, the Microcell LOS path loss with consideration of using the same previous assumptions [19] is given by

$$\mathrm{PL(L)} = 30.18 + 26\log_{10}(\mathrm{L}) \qquad \textbf{(2)}$$

Thus, it now becomes easier for the network provider to identify the appropriate locations of the installed Mobile-Femtos in current and future networks. The BH link between the Mobile-Femto and the eNB will be using the NLOS PL model in order to identify the ideal distance between eNBs and Mobile-Femtos. In contrast, a constant PL has been used for the LOS access link between Mobile-Femtos and their served UEs within the same train carriage. The Constant PL is a free-space loss when there is no barrier between the transmitted and received signals; however, there is always a -84.55 constant power loss [21]. This has made it clear that as much as it is needed to mitigate the path loss and penetration loss between train passengers and serving Mobile-Femtos; it is even more needed to maintain the BH link path loss between eNBs and Mobile-Femtos. This is because; maintaining strong connections between Mobile-Femtos and eNBs as well as between Mobile-Femtos and train passengers can greatly mitigate the impact of the generated interference.

However, the previous discussed coverage planning scheme might not fully mitigate the interference by itself as it should be combined with an appropriate transmission power to further reduce the interference and coverage holes.

2. Transmission Power control

Controlling the transmission power of eNBs and Mobile-Femto is a very important factor in current and future networks. As mentioned earlier; insufficient power transmission with poor Femtocell deployment leaves the network with dead zones (holes). On the other hand, if the Femtocell transmission power is high with dense Femtocells deployment, this can create excessive interference between the different parties within the network. The organised installation of Femtocells makes it easier to manage planning and dense distribution. Therefore, many researchers have considered the control of Femtocells transmission power as an efficient method for interference avoidance. Normally, for a short distance between the serving Femtocell and its UEs, low transmission power is required for communication. Consequently, researches showed that controlling the transmission power is an essential solution to avoid dead zones and power leakage between adjacent carriers in current and future networks. For that reason, optimal control of BS transmission power helps not only in enhancing the Macro and Femto UEs' performance but also in improving the indoor coverage. This transmission power should not be too low as it will limit the coverage area; in contrast, high transmission power could easily cause interference to other served UEs and BSs.

In the CCMF scenario, the channel between the Femtocell and its UEs is considered to be in a good state and less affected by the interfered signals from other BSs. This is due to the short distance between the transmitter and the receiver (Mobile-Femtos and their UEs). In addition to that, high penetration loss of the train environment (well shielded carriages) prevents outside signals from passing through to train passengers. This makes it clear that train carriage chassis can work as a barrier to isolate the train passengers from the outside signals. This assures that train passengers will be served only by the installed Femtocell (Mobile-Femto) within their carriage; as a result, the interference can be mitigated.

Accordingly, installing Mobile-Femtos in their right positions based on the used path loss model and controlling their transmission power play important role in mitigating interference and filling coverage holes which has already been shown in our previous work [22]. The achieved results lead to the conclusion that choosing low transmission powers has a negative impact on achieved throughput and the number of scheduled UEs even when the interference is mitigated. In contrast, choosing high transmission powers has even more negative impact on the throughput and number of scheduled UEs as a result of severe generated interference that could easily take down the entire network performance.

The previous two possible solutions have been used for years by service providers to provide their users with the quality of services they are paying for and reduce the impact of the generated interference. However, there are always worst case scenarios as a result of the high mobility which makes it even more challenging to control interference. This is because; in such vehicular environment where Mobile-Femto is installed, there are unexpected scenarios that could always take a place in unpredictable manner. Therefore, to overcome such scenarios, the following interference mitigation scheme is presented in this paper and discussed thoroughly to show its positive impact on the network and UEs' performance.

3. Proposed Interference Management Scheme

In order to meet the requirements of CCMFs deployment, the Fractional Frequency Reuse (FFR) scheme has been presented. This scheme is one of the solutions that have been introduced to reduce the impact of Inter Cell Interference (ICI) in the Macrocell system, precisely more for the cell-edge UEs. It also helps to achieve reuse factor of one for the Macrocell center zone while higher reuse factors are being adapted by edge zones. The ICI is substantially reduced and the system throughput is improved. Subsequently, the generated interference caused by the dense deployment of Femtocells should be minimised for both; Macro and Femto UEs. The FFR interference mitigation scheme works very well with the CCMFs deployment as the Mobile-Femto chooses frequency sub-bands that have not been used by the Macrocell nor other Mobile-Femtos.

Fig5 illustrates the proposed scheme in more detail and it clearly shows how the frequency sub-bands allocated between Macrocells and Mobile-Femtos. The scheme divides the Macrocell coverage into a center zone and edge zone. F_0 sub-band is allocated for the center zone of the three Macrocells, whereas F_1, F_2 and F_3 are assigned to the edge zones of $Macrocell_1$, $Macrocell_2$ and $Macrocell_3$ respectively. Thus, applying the frequency reuse scheme in vehicular environment has its own positive impact on network performance. This is because Mobile-Femto will be allocating frequency sub-bands that have not been used by Macrocells of other Mobile-Femtos.

For example, if there is a Mobile-Femto moving in the cell edge of $Macrocell_2$, F_0 or F_1+F_3 can be allocated by the edge Mobile-Femto to serve its UEs. On the other hand, if the Mobile-Femto is moving in the central zone of $Macrocell_2$, then sub-band F_1+F_3 is applied. It is to be mentioned that, sub-band F_0 cannot be used by this Mobile-Femto because it is already being used by the serving $Macrocell_2$ in the central zone. Additionally, sub-band F_2 which is being used by $Macrocell_2$ to serve its cell edge Macro UEs cannot also be used by that Mobile-Femto located in the central zone. This is due to the eNB transmission power differences between edge and center zones to suite each serving case. The center UEs close to the eNB require lower transmission power in comparison to the cell edge UEs who require maximum transmission power from the eNB to satisfy their UEs service needs. The previous approach has its positive impact on avoiding the generated interference between transmitted signals.

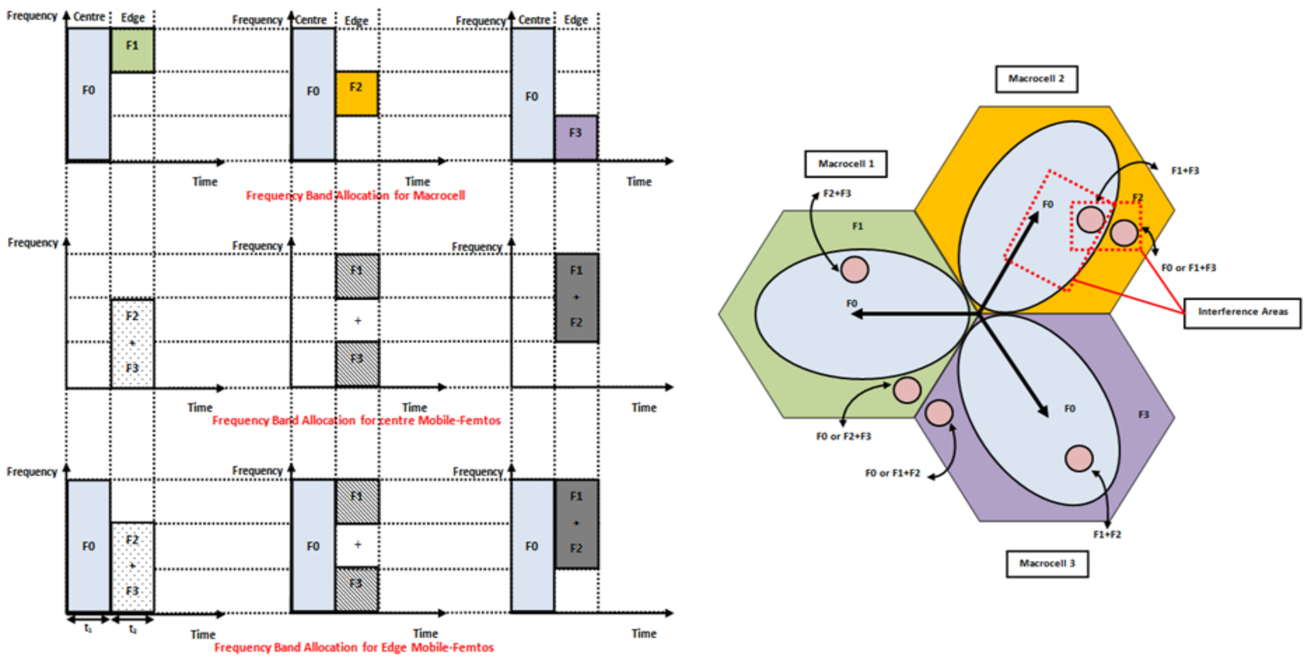

Fig.5.The proposed interference management scheme based on the FFR

This is because; different subcarriers are allocated and assigned to Mobile-Femtos and eNBs UEs based on Macrocell zones to improve UEs performance and signal services.

While in order to avoid interference between the CCMF themselves, service providers can use the same frequency reuse approach discussed earlier. In that case, every Mobile-Femto inside the train carriage will be using frequency sub-bands that have not been used by neighboring Mobile-Femtos but can reuse the frequencies of further Mobile-Femtos that would not cause interference to its served UEs.

In real life scenarios this frequency reuse scheme works by receiving Macrocell dimensions, Mobile-Femtos numbers and locations based on train paths. More network characteristics are required like BS transmission powers, received power from serving and interfering cells calculations and the white Gaussian noise. Hence, based on the pervious values, the scheme is now able to estimate for SINR and throughput at any given position in the serving network. Accordingly, the proposed frequency reuses scheme works as detailed below:

a) Inner cell radius calculations

Based on the Macrocell characteristics and the used transmission powers, the inner cell radius is calculated to differentiate between centre and cell edge zones as Fig6 illustrates.

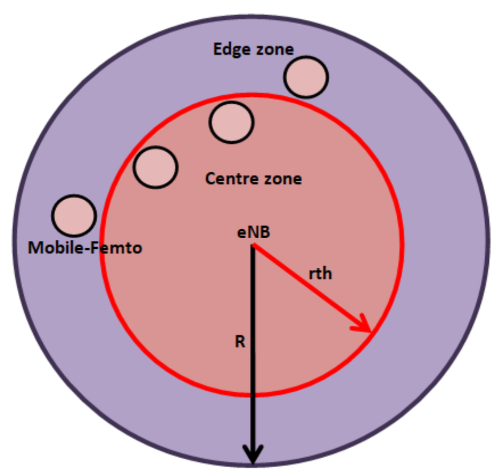

Fig.6.Inner cell radius

b) Optimum frequency band division

This step is more concerned with calculating the SINR and throughput of served UEs with every possible combination of spectrum division. The radio spectrum is divided into frequency sub-bands reserved for a single or range of compatible users. The sub-bands use individual transmitters with separate frequencies or channels to avoid any sort of interference. Thus, the available spectrum is allocated to UEs in a way that maximises their obtained throughput. Accordingly, the subcarriers consist of two disjoint sets; centre and edge-zones subcarriers. The cell edge zone subcarriers divides the frequency to three sub-bands; F_1, F_2 and F_3. So, if the set of the centre zone is assumed to be an empty set and all subcarriers are allocated to the cell edge set with $Total_{subcarriers}/3$. Each and every time, one subcarrier is removed from the cell edge zone set and added to the centre zone set. As a final stage, the centre zone set will have $Total_{subcarriers}$ and the cell edge zone set will be an empty set until this process repeats itself over and over to reuse frequency sub-bands every time.

c) Mobile-Femtos frequency bands allocations

The Mobile-Femtos frequency bands allocation is being done according to the process presented earlier in Fig6, and the entire frequency reuse scheme is summarised according to algorithm1.

Algorithm1: Frequency Reuse Interference Management for Macrocell/Mobile-Femtos

```
create_Networktopolgy();        /*defines network BSs and UEs
 for r = 0: R                   /*inner cell radius
for f = 0: Total-subcarriers    /*frequency band division
allocate frequency band for macrocells;
   if r > = distance_mfemto   /*Mobile-Femto belongs to center zone
            allocate frequency band for mfemto;
   else if  r <  distance_mfemto   /*Mobile-Femto belongs edge  zone
            allocate frequency band for mfemto;
   end
   end
for u = 1 : U                   /*For all UEs calculate
sinr = calculate_sinr(u)
capacity = calculate_capacity(u)
throughput = calculate_ throughput(u)
end
end
end
define_FFR(max_ user_throughput)
```

IV. SYSTEM LEVEL

In order to study the impact of the proposed interference management scheme on UEs performance, the SINR, throughput and capacity will be formulated in this work. The Macro and Mobile-Femto UEs can be interfered by the DL/UL signals of neighboring eNBs and Mobile-Femtos. Therefore, on subcarrier n the received Macro UE SINR is given by

$$\mathrm{SINR}_{m(D),n} = \frac{P_x^{eNB}\left|G_{1,eNB,n}\right|^2 PL(x)\varepsilon}{\sum_{eNB'=1}^{neNB'} P_x^{eNB'}\left|G_{1,eNB',n}\right|^2 + \sum_{MFemto=1}^{nMFemto} P_x^{MFemto}\left|G_{2,MFemto,n}\right|^2 + P_{noise}} \quad \textbf{(3)}$$

where P_x^{eNB} and $P_x^{eNB'}$ represent the serving eNB and the neighbouring eNB' transmission powers on subcarrier n respectively. The $G_{1,eNB,n}$ is the channel gain between the Macro UE m and serving eNB while the channel gain from neighbouring eNBs is denoted by $G_{1,eNB',n}$. P_x^{MFemto} is the transmission power of neighbouring Mobile-Femtos, $G_{2,MFemto,n}$ is the channel gain between the Macro UE m and neighbouring Mobile-Femto. The Path Loss model has already been calculated in this work and it is expressed by PL where x is the distance between the Macro UE and its serving eNB. The VPL is represented by ε and the white noise power is represented by P_{noise}. Hence, equation (3) has made it clear that Macro UEs can be interfered by two interference sources, neighbouring eNBs signals and Mobile-Femtos signals.

As well as in the previous case, Mobile-Femto UEs can be interfered by eNB signals or any neighbouring Mobile-Femto signals. Consequently, on subcarrier n the received Mobile-Femto UE SINR is given by

$$\mathrm{SINR}_{mf(A),n} = \frac{P_x^{MFemto} C_{loss}}{\sum_{eNB=1}^{neNB} P_x^{eNB}\left|G_{1,eNB,n}\right|^2 + \sum_{MFemto'=1}^{nMFemto'} P_x^{MFemto'}\left|G_{2,MFemto',n}\right|^2 + P_{noise}} \quad \textbf{(4)}$$

In equation (4), there is only a constant system loss since there is no channel gain over the LOS access link with the served Mobile-Femto UEs. It is to be mentioned that, the only existing channel gain ($G_{2,MFemto',n}$) is between the Mobile-Femto UEs and other neighbouring Mobile-Femtos.

In contrast, on subcarrier n, the Macro UEs capacity can be calculated as [23]

$$C_{m,n} = BW.\log_2(1 + \alpha \mathrm{SINR}_{m(D),n}) \quad \textbf{(5)}$$

where the divided bandwidth for subcarrier n is represented by BW and α is a constant coding margin for target Bit Error Rate (BER) which is given by α = -1.5/ln(5BER) [24]. As a result, the overall throughput of the serving eNB M is given by

$$\mathrm{Throughput}_M = \sum_m \sum_n \beta_{m(D),n} C_{m(D),n} \quad \textbf{(6)}$$

where $\beta_{m,n}$ represents the assigned subcarrier for Macro UEs. So when $\beta_{m(D),n} = 1$, the subcarrier n is assigned to Macro UE m, otherwise $\beta_{m(D),n} = 0$. It is to be mentioned that, every Macro UE in every time slot is allocating different subcarrier within the same Macrocell. The $\sum_{m=1}^{N_m} \beta_{m(D),n} = 1$ for ∀k as N_m is the Macro UEs number and k is the available PRBs. In contrast, similar expression is given for the Mobile-Femto UEs associated with the calculated capacity and throughput. However, the expected $\sum_{mf=1}^{N_{mf}} \beta_{mf(A),n} = 3$ for $k \in F_{Mobile\text{-}Femto}$ where the Mobile-Femto UEs number is represented by N_{mf} and the available sub-bands allocated to Mobile-Femtos is represented by $F_{Mobile\text{-}Femto}$. This makes it clear that the proposed scheme reuses the full frequency bands three times in every Macrocell.

As a consequence, the capacity of the Mobile-Femto UE on subcarrier n can be expressed as

$$C_{mf,n} = BW.\log_2(1 + \alpha \mathrm{SINR}_{mf(A),n}) \quad \textbf{(7)}$$

On the other hand, the overall throughput of the serving Mobile-Femto can be given by

$$\mathrm{Throughput}_{MFemto} = \sum_{mf} \sum_n \beta_{mf(A),n} C_{mf(A),n} \quad \textbf{(8)}$$

After discussing the important factors that have the biggest impact on the UE and network performance, the subsequent results will show that the proposed scheme is greatly capable of preventing the interference among the Macro and CCMFs UEs.

V. Results And Discussion

A system-level simulation via MATLAB software has been used to evaluate the network performance before and after implementing the proposed frequency reuse interference mitigation scheme. Fig7 illustrates the network topology and the train path where the CCMFs will be installed in the train carriages. It is to be mentioned that the x-position of the tracks does not change as we have chosen on purpose the train to be at the cell edges of the Macrocells.

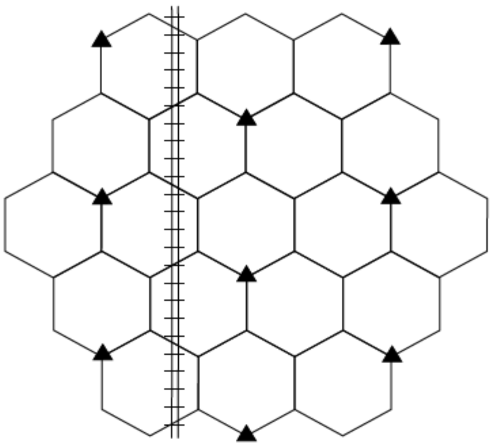

Fig.7.Network layout

Table1 represents some of the considered parameters for simulating the required environment and scenarios.

Table1 Simulation parameters

Parameter	Value
System bandwidth	10MHz
Traffic module	Full buffer
Mobile-Femto type	In-band, full duplex
Cells number	19
Numer of Macro UEs	10
Number of carriages in the train	5
Number of BH links in the train	5
Number of Mobile-Femto UEs	1-5
Train position	Cell edge
VPL	10-40dB
Mobile-Femto transmission power	0-20dBm (DL)
Cell edge UE PL	PL > 120dB

In this work, the performance of the DL and UL UEs with and without the implementation of the proposed interference scheme in the CCMFs environment was assessed.

A) Downlink

Fig8 illustrates the gain of cell edge UE's throughput in train carriages when the proposed interference management scheme is applied for DL with consideration of VPL and MFemto transmission power. The achieved results show that the gain is greater for small MFemto transmission powers and small VPLs -compared to the case without the use of the proposed scheme -. In this case, the interference from the Macro network is at its highest as the low VPL does not isolate the indoor UEs from outdoor interference signals. However, high penetration loss provides a natural protection against outside interference, and especially for high transmission power, thus, the gain from the proposed scheme is very low (since the SINR is high.)

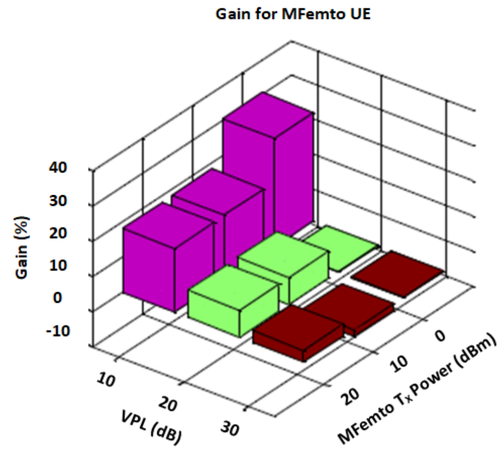

Fig.8.Vehicular UE's gain

Fig9 clearly shows that using the proposed interference management scheme does not degrade the Macro UE's performance. The loss depends on the used parameters, but at most it is about 3%.

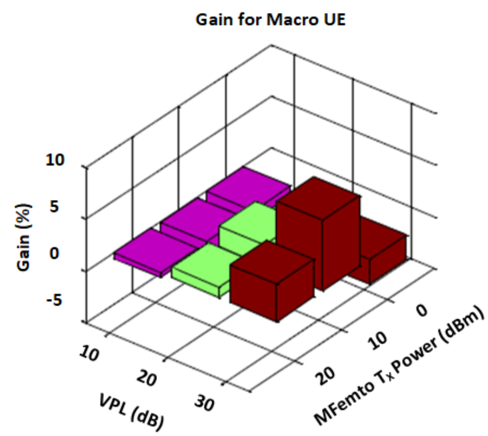

Fig.9.Macro UE's gain

B) Uplink

Fig10 shows the UL Macro UE's performance with and without the proposed scheme. As stated earlier, the average number of Macro UEs per cell has been considered to be 10 users while the train path is located at cell edges. All BH links are defined as cell-edge UEs. This is because; those BH links are in charge of linking the CCMFs with the serving Macrocells, thus, being able to serve those train passengers. As shown earlier in this work, the cell edge UEs are defined by the calculated path loss model. The figure also shows the performance of the network without the Macro UE Transmit Power Control (TPC). As expected, TPC improves the cell-edge Macro UE performance, and the Proposed frequency-reuse Interference Mitigation Scheme (PIMS) improves this even further.

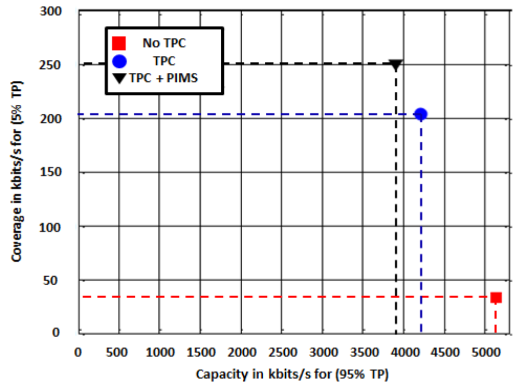

Fig.10.UL performance of Macro UEs with the proposed scheme and 10 Macro UEs

Fig11 illustrates the performance for train passengers which we call Mobile-Femto UEs. For comparison purposes, the case without proposed scheme is also shown.

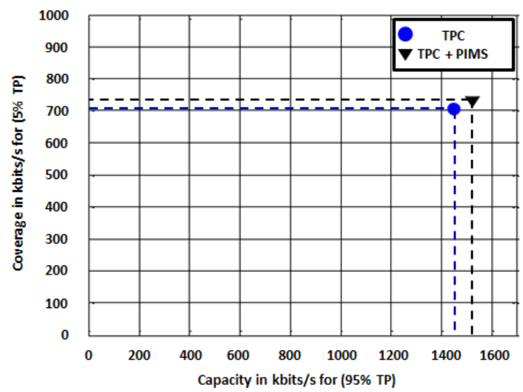

Fig.11.Vehicular UL performance with the proposed scheme and 10 Macro UEs

The results show the improvement in both Macro and Mobile-Femto UE performance after the implementation of the proposed scheme. However, with the proposed scheme, the 95% throughput of macro UEs is slightly deteriorated. This is due to the fact that cell-edge UEs are given priority in PRBs allocation while leaving fewer options for the Macro UE. This in fact a characteristic of most FFR methods, which are more concerned with improving the cell-edge UEs performance. In the UL simulations, 10 macro UEs were assumed per cell; however, according to the 3GPP recommendations and simulation assumptions [25], there should be an average of 25 UEs per cell. Therefore, the simulation was repeated with 25 UEs per cell. The results are shown in Fig12 and Fig13 for Macro UEs and train passengers respectively. When the 95% performance of Macro UEs and Mobile-Femto UEs are being compared, it has clearly been noticed the large difference in the achieved performance between the two. This is due to the fact that the BH capacity is divided between the Mobile-Femto UEs inside the train carriages where each user gets an equal share. Furthermore, the proposed scheme does not degrade the 95% transmission power compared to the case without the proposed scheme. The reason is that, the proposed scheme improves the BH performance; since the BH links are always being treated as cell edge UEs, giving them an advantage.

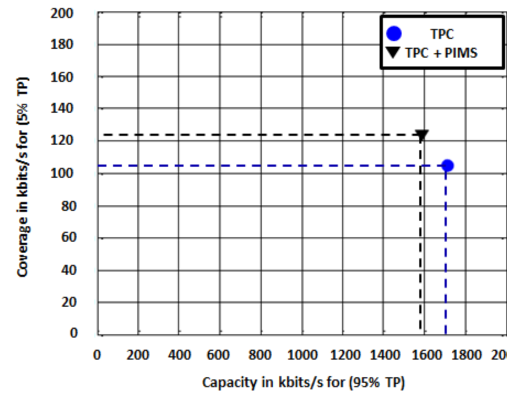

Fig.12.UL performance (Macro UEs) with the proposed scheme and 25 Macro UEs

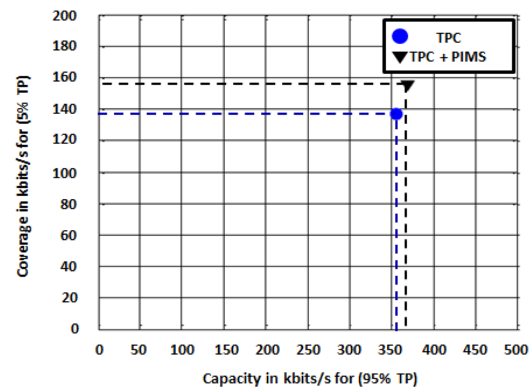

Fig.13.UL performance (vehicular UEs) with the proposed scheme and 25 Macro UEs

VI. Conclusion

The future of the railway industry is expected to rely upon smart transportation systems that provide train passengers with new services. These smart railways are more into improving the users experience when they are using public transportation. Small cells (e.g. CCMFs) were the optimal solution to offer internet services inside train carriages for train passengers. However, every technology comes with its challenges and the main two challenges in such environment are mobility and interference. Therefore, in terms of mobility a group HO procedure was presented to save network resources; on the other hand a frequency reuses scheme was introduced to mitigate the generated interference in such environment. All achieved results make it clear that using the CCMFs system in trains is a good method to boost the performance of UEs inside train carriages, as it eliminates VPL. The proposed mobility and interference mitigation schemes work perfectly with the deployment of the CCMFs in HSTs environment. This is because deploying new technologies needs new methods and techniques to eliminate the raised issues with introducing such technologies.

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References

[1] R. Raheem, A. Lasebae, M. Aiash, J. Loo, R. H Colson, "Mobile Femtocells utilisation in LTE vehicular Environments: Vehicular Penetration Loss Elimination and Performance Enhancement", *ELSEVIER Journal on Vehicular Communications,* 2017.

[2] R. Raheem, A. Lasebae, M. Aiash and J. Loo, "Mobility Management for Vehicular User Equipments in LTE/Mobile Femtocell Networks", *International Journal of Information Systems in the Service Sector (IJISSS),* 2017.

[3] B. Ai, R. He, Z. Zhong, K. Guan, B. Chen, P. Liu and Y. Li, "Radio Wave Propagation Scence Partitioning for High-Speed Rails", Hindawi, International Journal of Antennas and Propagation, 2012.

[4] Shift2Rail, "Rails Proejcts", accessed at: http://www.shift2rail.org, accessed on 17/08/2018.

[5] Z. D. Zhong, "Key Issues for GSM-R and LTE-R", Beijing Jiaotong University and Springer-Verlag GmbH Germany, Dedicated Mobile Communications for High-speed Railway, Advances in High-speed Rail Technology, DOI 10.1007/978-3-662-54860-8_2, 2018.

[6] METIS project, Deliv. D1.1, "Scenarios, Requirements and KPIs for 5G Mobile and Wireless System," tech. rep., Apr. 2014.

[7] 5GNow, 5th Generation Non-Orthogonal Waveforms for Asynchronous Signalling, accessed on: 20/08/2018, available at: http://www.5gnow.eu.

[8] UIC, UIC Projects, Available at: https://uic.org/uic-projects, accessed on 24/08/2018.

[9] HORIZON 2020 Work Programme 2014–2015 11. Smart, Green and Integrated Transport Revised, EC Decision C(2014)4995, July 2018.

[10] P. N. Vivas, C. Campo, C. G. Rubio and A. R. Carrion, "Communication Technology for Vehicles", 4th International Workshop, Nets4Cars/Nets4Trains, Vilnius, pp 174-185, 2012.

[11] I. Kostanic, "Link budgets and nominal cell planning", accessed on: 24/08/2018, available at http://slideplayer.com.

[12] S. Scott, J. Leinonen, P. Pirinen, J. Vihriala, V. V. Phan and M. Latva-aho, "A Cooperative Moving Relay Node System Deployment In A High Speed Train", Center for Wireless Commun., Univ. of Oulu, Oulu, Finland, 2013.

[13] 3G4G Small Cells Blog, "Small Cells on the Train – A 2 hop solution", Available at: http://smallcells.3g4g.co.uk/2015/07/small-cells-on-train-2-hop-solution.html, Accessed on: 24/08/2018.

[14] S. Chae, T. Nguyen and M. Y. Jang, "A Novel Handover Scheme in Moving Vehicular Femtocell Networks", Department of Electronics Engineering, Kookmin University, Seoul 136-702, Korea, 2013.

[15] M. S. Pan, M. Lin and W. T. Chen "An Enhanced Handover Scheme for Mobile Relays in LTE-A High-Speed Rail Networks", IEEE Transactions on Vehicular Technology, Vol. 64, No. 2, Feb 2015.

[16] R. Raheem, A. Lasebae and J. Loo, "Mobility Management in LTE/Mobile Femtocell Networks: Outage Probability and Drop/Block Calls probability", *IEEE 3rd International Conference on Emerging Research Paradigms in Business and Social Sciences (ERPBSS-2015), Dubai, United Arab Emirates, 2015.*

[17] T. Ma and P. Pietzuch, "Femtocell Coverage Optimisation Using Statistical Verification" accessed on: 26/08/2018, available at: http://lsds.doc.ic.ac.uk.

[18] Z. Lu, T. Bansal, P. Sinha, "Achieving User-Level Fairness in Open-Access Femtocell based Architecture", Mobile Computing, IEEE transactions, pp.1943-1954, 2012.

[19] Y. A. Alqudah, "On the performance of Cost 231 Walfish Ikegami model in deployed 3.5 GHz network", in proc. of technological Advances in Electrical, Electronics and Computer Engineering (TAEECE) International Conference, Konya, 2013.

[20] Naguib A., "Channel Models for IEEE 802.20 MBWA System Simulations – Rev 08r1", IEEE 802.20 Working Group on Mobile Broadband Wireless Access, 2007.

[21] H. Masui, T. Kobayashi and M. Akaike, "Microwave path loss modelling in urban line-of-sight environments," IEEE J. Sel. Areas Commun., vol. 20, pp. 1151–1155, Aug 2002.

[22] R. Raheem, A. Lasebae, M. Aiash, J. Loo and R. H Colson "Interference Management and System Optimisation for Femtocells Technology in LTE and Future 4G/5G Networks", Advances in Communications: Reviews' Book Series, Vol. 1, IFSA Publishing (Barcelona, Spain) in 2017.

[23] Lee P., Lee T., Jeong J., and Shin J., "Interference management in LTE femtocell systems using fractional frequency reuse", International Conference on Advanced Communication Technology (ICACT 2010), Phoenix Park, Korea (pp. 1047-1051).

[24] Nungu A., Pehrson B. and Sansa-Otim J., "e-Infrastructure and e-Services for Developing Countries", Springer publisher, the 6th International Conference, AFRICOMM, Kampala, Uganda, 2014.

[25] 3GPP TR 36.814 V9.0.0 Technical Report, 3rd Generation Partnerships; technical Specification Group Radio Access Network; Evolved universal terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects (Release 9), 2010.