Exploiting Femtocellular Networks for Emergency Telemedicine Applications in Multiple Dwelling Units

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Abstract

This paper presents a proposal for a solution for rapid provisioning of broadband connectivity for emergency telemedicine applications in indoor environments. The proposed solution relies onthe exploitation of existing femtocellular network resources available in the site of the emergency. Extensive simulations are carried out to compare the performance of the proposed femtocellular approach to the conventional macrocellular mobile networking approach. The simulation results indicate at least an order of magnitude reduction in service outage rates when femtocells are utilized in the comparison to the macrocellular case for buildings on the cell edge.

Keyword: Emergency telemedicine; femtocells; 3G mobile networks

I. Introduction

Telemedicine or telehealth may be defined as the process using telecommunications and information technology to support the real-time delivery of specialist medical services at remote locations. In the case of emergency or trauma patients, they would typically require rapid, definitive and precise pre-hospital care as well as advanced resources and continuous medical expertise for the duration of the emergency state [1]. To that end, emergency telemedicine would enable an experienced trauma surgeon or physician to be virtually present and assist paramedics or less experienced physicians at a remote emergency scene.

In order to meet the aforementioned requirements for delivery of emergency medical services, emergency telemedicine would preferably be implemented over an existing broadband wireless network infrastructure. This is natural evolution from early emergency telemedicine systems that employed mobile radio for enabling conversational voice and low-rate data telemetry between sites of emergency, receiving hospitals or trauma centers and emergency dispatch centers [2]. The availability of broadband wireless networks opens up the possibility of high-resolution medical scan image transfer, high-volume biosignal data telemetry, streaming video, videoconferencing, location-based services and other rich multimedia services, that greatly enhance the delivery of emergency medical services.

A. Broadband Wireless Networks for Emergency Telemedicine

Several candidate wireless networking technologies are now utilized for implementing emergency telemedicine systems, albeit with some notable limitations. Authority-owned professional mobile radio (PMR) networks (usually based on the TErrestial Trunked RAdio or TETRA standard) possess the security, robustness and service prioritization that is usually demanded by emergency response organizations in life- or mission-critical operations [3].

However, the maximum achievable data rates for contemporary digital PMR networks are relatively limited in comparison to commercial systems. For instance, TETRA Release 1 standards define a maximum achievable data rate of 28.8 kbps for 25 kHz channel bandwidth, suitable only for voice, low-speed data and slow-scan video services. The subsequent TETRA Release 2 standards, commonly referred to as TETRA Enhanced Data Services (TEDS), specified air interface enhancements that provide an order of magnitude improvement in achievable data rates compared to TETRA Release 1 [4]. Unfortunately, TEDS implementations are still rare due to difficulties in obtaining an internationally harmonized spectrum band and the unacceptably high total cost of ownership for TETRA network deployments at higher spectrum bands (above 1 GHz) [5].

Therefore, emergency response organization would now resort to utilizing commercial public 2.5G or 3G mobile networks for services that would typically require data rates higher than those achievable by TETRA [6]. This trend is supported by the increased commercial availability of multisystem user devices equipped with TETRA and non-TETRA interfaces, which enable the user to leverage the capabilities offered by both public mobile and PMR networks. Furthermore, the continued evolution beyond 3G (e.g. High-Speed Packet Access [HSPA]) will provide data rates significantly above 384 kbps, easily exceeding the feasible TEDS data rates. However, in practice the conventional macrocellular 3G (or above) mobile networks may only guarantee data rates well below achievable maximum depending on various factors, such as, the instantaneous network traffic or load patterns and throughput deterioration at cell edges. Moreover, poor indoor coverage (e.g. due to wall penetration losses) would further degrade the achievable performance of 3G networks.

B. Complementary Femtocellular Approach Emergency Telemedicine

Recently, indoor solution based on femtocellular networks has been proposed in order to provide ubiquitous coverage for in-building communications [7] [8]. Femtocellular networks consist of inexpensive Home Base Station (HBS) or Home Node B that units that can be deployed autonomously in a private residential or business premises by a user in the same plug-and-play mode as digital subscriber line (DSL) or cable modems. The HBS equipment would typically be owned by the user, and configured to provide access to a restricted group of users, e.g., family or household members who form the so-called Closed Subscriber Group (CSG). Alternatively, if CSG is not used, HBS allows open access to all subscribers of the operator. Therefore, from the perspective of emergency telemedicine implementations, the femtocellular approach promises the benefit of improved coverage for providing emergency medical services in indoor environments, possibility of configuring even CSG femtocellular networks to be accessed by emergency response personnel and at least an order of magnitude improvement in capacity gains compared to purely macrocellular network implementation [7].

In this paper we carry out a simulation study on exploiting existing femtocellular network capacity for emergency telemedicine applications. Specifically we focus on the case whereby paramedics providing emergency medical services are to exploit the femtocellular capacity available from the patients' or the neighbourhood HBS in a multiple dwelling unit (MDU) indoor environment. Section 2 describes the usage scenario in more detail while Section 3 outlines the system model. The simulation results are discussed in Section 4 and conclusions provided in Section 5. It should be noted that while the focus of this study is on the emergency telemedicine use case, the proposed femtocellular approach and study results are equally applicable for other emergency response applications (e.g., fire, police etc.) within an indoor environment.

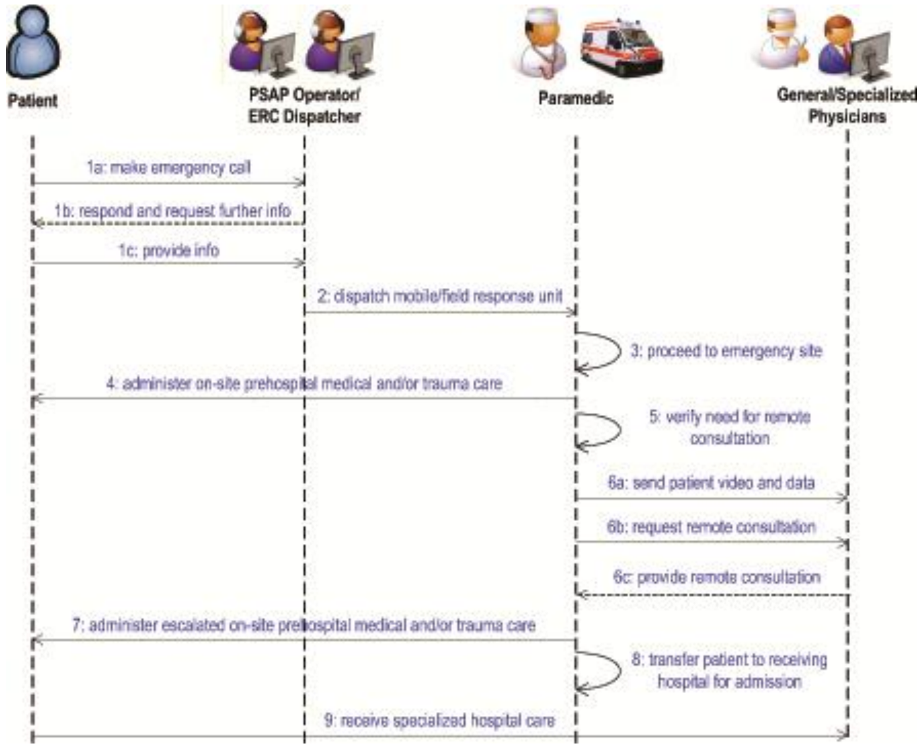

Fig. 1. Use case description sequence diagram

II. STUDY CASE DESCRIPTION AND ASSUMPTIONS

A. Use Case Scenario Description

The complete use case scenario description for our study is depicted in Fig. 1. We propose the usage of locally available femtocellular network resources to support emergency telemedicine supported activities 6a-6c of Fig. 1, performed at the initial location of emergency and prior to patient transfer via ambulance. This would for instance enable paramedics to setup a videoconferencing session with a physician at the receiving hospital or other remote consultation site. Furthermore, the paramedics could simultaneously send telemetric biosignal measurements (e.g. electrocardiogram time series data) and medical image scans to provide the physician with a real-time awareness of the patient’s condition and support their decision-making process. Trauma device platforms and software clients providing an environment for running simultaneous applications (e.g., data, video, images) have been previously demonstrated [6].

The emergency location of the patient considered in the study is an indoor residential environment of multiple dwelling units (MDUs) structured as homes or apartments in a mid/high-rise with each floor having multiple apartments. Furthermore, the simulation study is repeated for MDUs structured as terraced (horizental) buildings with multi-floor apartments(typically two floors per apartment). The rationale behind the selection of these MDU types is that ccount for over half of all the residential dwelling types in the country of study, Finland [9].

B. System Architecture

The end-to-end system architecture illustrating the key network components and main actors in the femtocellular emergency telemedicine system is shown in Fig. 2. In a MDU environment, HBSs are deployed in a certain fraction of the apartments in the building, with the actual number of HBSs in a building being approximated according to some assumed HBS adoption trends. The HBS are then connected to the Femto Gateway of the operator using the local residential broadband Internet access link (e.g., DSL, fiber-to-the-premises) for backhaul. The Femto Gateway services up to hundreds of HBS units, which forwards the data to operator network or Internet. Therefore, paramedics are able to obtain broadband Internet access with suitable Quality of Service (QoS) guarantees by connecting to the HBS in patient's home or overlapping coverage from a HBS of one the neighboring apartments. In the absence of sufficient HBS femtocellular coverage, connection to macrocellular base station (MBS) is assumed.

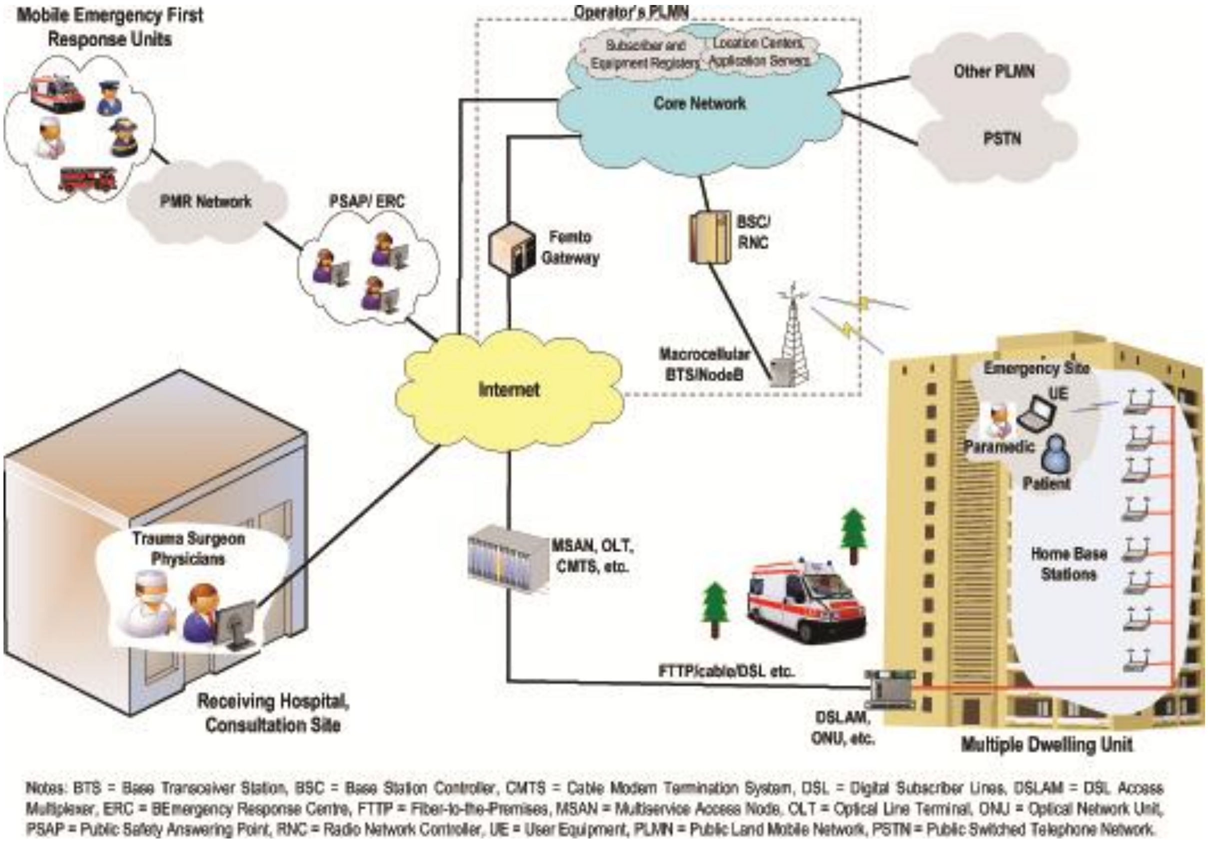

Fig. 2. General system architecture

In our study we assume ideal performance over local fixed backhaul link and focus on the simulation of the essential effects of non-line-of-sight RF signal propagation in the considered environment. This includes effects such as free space path loss, fading, attenuation through walls and windows, co-channel interference from other RF transmitters and indoor multipath propagation.

III. SYSTEM MODEL

A grid-layout building structure is assumed for both multi-floor apartment block and terraced houses. As shown in Fig. 3, indoor user equipments (UE) shown as circles are uniformly distributed within the building. And femtocell shown as square is assumed to be attached to the wall of its residing apartment/house. In each apartment/house, femtocell penetration rate P_{femto} determines the probability that there exists a femtocell. In our cases, femtocells are assumed to reuse the same frequency band as macrocells and grant only CSG access to indoor UEs. Simulation parameters including path loss model, antenna model, dimensioning and service parameters are summarized in Table I and II.

TABLE I

SIMULATION PARAMETERS

The number of indoor UEs is *24* for multi-floor apartments block, and *10* for terraced houses. Target uplink load factor of macrocell is *0.5* with other-cell to own-cell interference ratio is *0.5*
Indoor path loss is modeled as $98.5+20\ log_{10}(R)+L_{wall}$ plus a log-normal distributed shadow fading with 4dB standard deviation, where R in km and L_{wall} is *8/15/20*dB for light/internal/outer wall respectively. Indoor-to-outdoor path loss is modeled as [10] $PL=Pr(R)PL_{LOS}(R)+(1-Pr(R))PL_{NLOS}(R)+L_{wall}$, where $PL_{LOS}(R)=103.8+20.9\ log_{10}(R)$ $PL_{NLOS}(R)=145.4+37.5\ log_{10}(R)$ $Pr(R)=0.5-min(0.5,\ 5\ exp(-0.156/R))+min(0.5,\ 5\ exp(-R/0.03))$ plus a log-normal shadow fading with *10*dB standard deviation.
The macrocell antenna gain is calculated as $G(\theta) + G_{max} - min(12(\theta/\theta_{3dB}),G_s),\ -\pi\leq\theta\leq\pi$, where θ_{3dB} = 70 degrees, G_s = 20dB and G_{max} = 16dB

TABLE II

INDOOR UES SERVICE CONSTITUTION RATIO

	Voice	144kbps data	384kbps data
MUE(100m)	90%	10%	0
MUE(300m)	100%	0	0
HUE	40%	20%	40%
Target Eb/N0	4,5dB	2dB	2dB

As depicted in Fig. 4, the indoor and indoor-to-outdoor signal propagations are explicitly modeled, i.e. the path losses caused by free-space path loss, wall attenuation, shadowing and fast fading are considered between each indoor transceiver pair. And all the indoor UE interferences are included in the uplink power control procedure. The total uplink interference at femtocell from outdoor UEs is modeled as a random variable generated from its distribution which is calculated from simulation result. At macrocell base station (MBS), the total interference level from macrocell UE (MUE) can be parameterized by uplink load factor [11] given by (1).

(1)

where I_{total} is total interference power received by MBS and is given by

(2)

where I_{out} is outdoor MUE interference level received by MBS, Iin is indoor interference power level and P_N is noise power level. η is macrocell uplink load factor, i is other-cell to own-cell interference ratio and η_{ref} is uplink load coming from reference cell and given by

(3)

thus, substituting (2) and (3) in (1) gives

(4)

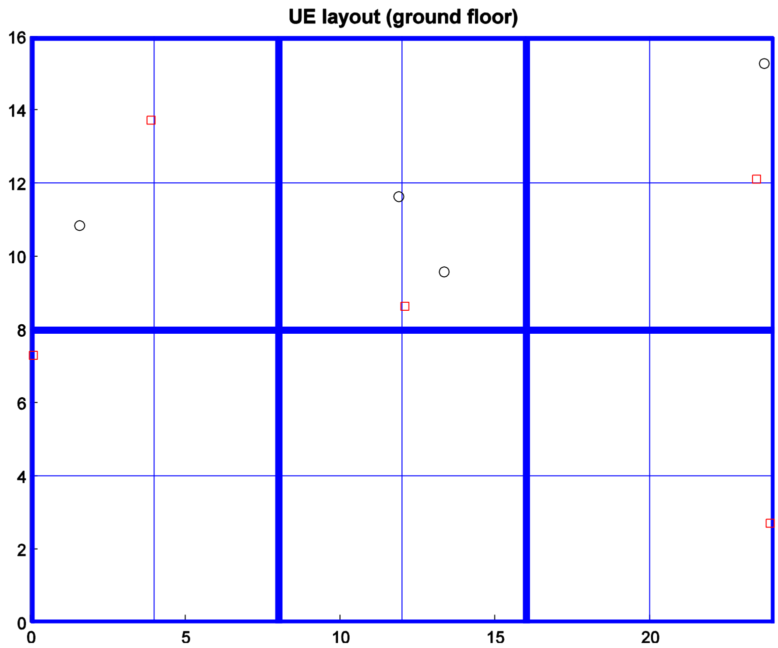

Fig. 3. Example of a 3×2 grid floor layout belonging to a multi-floor apartments block

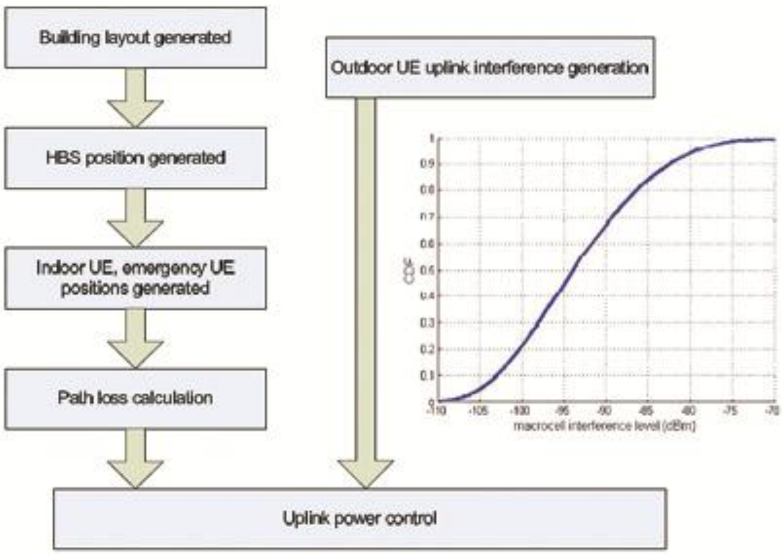

Fig. 4. Simulation block diagram

The inequality in (4) comes from introducing a term $\eta_{in}\eta_{out}$ in denominator and a term $-2\eta_{in}\eta_{ou}$ in numerator. This variation could be kept sufficiently low, if the target uplink load η is set to be 0.5. As a result, the total interference from outdoor MUEs can be modeled by

(5)

Furthermore, we assume that the emergency UE (EUE) requires three parallel data connection each of of 384 kbps in order to setup simultaneous emergency multimedia (image, conversational video, real-time data) sessions resembling that of [4]. In practice, adaptive radio resource management methods may be used to improve performance of the connections and maximize resource utilization efficiency. Therefore, by ignoring radio resource management schemes in our simulations, the simulation results presented in this paper provide the lower bound of the achievable EUE performance for both the MBS and HBS case. Moreover, the EUE retains a high priority by default, meaning its serving BS can only provide voice services to other UE sharing the same resources.

IV. Simulation Results

Our simulation compares the cumulative distribution functions (CDF) of EUE uplink transmission power in the cases (a) where EUE can be granted access to both MBS and HBSs, (b) where EUE can be only access to HBSs, and (c) where EUE can be only access to MBS. Results also show the uplink performance differences between the cases when buildings are within the high data rate service range of MBS and when buildings are at the macrocell edge. Outage events are shown by CDFs where uplink transmission power of EUE exceeds the maximum transmission power (21dBm).

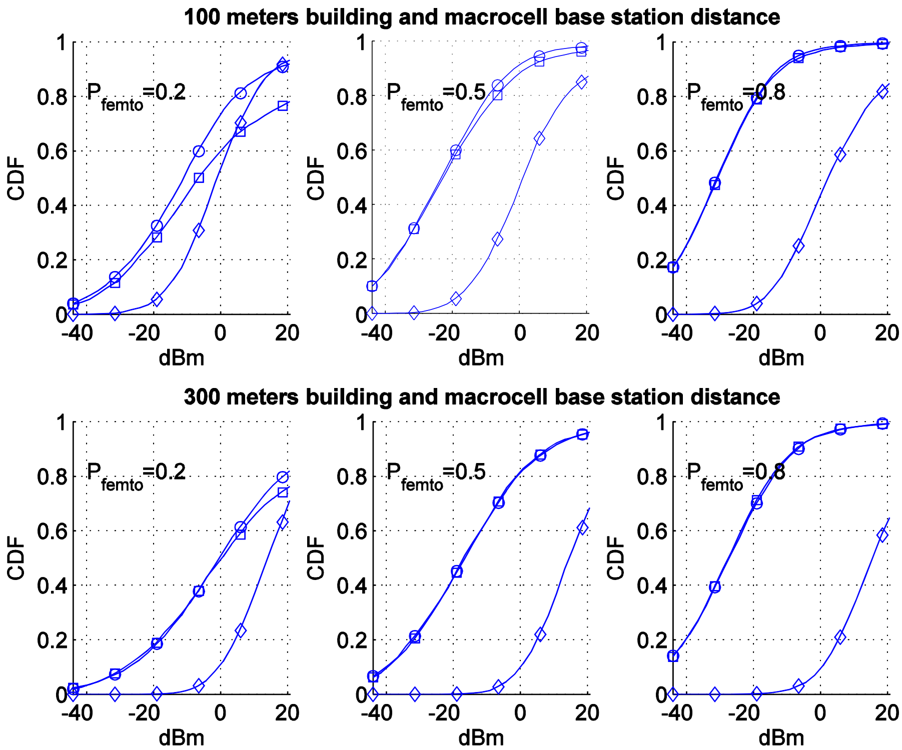

Fig. 5. CDFs of EUE transmission power in multi-floor apartment block. Line with circle denotes both MBS and HBSs are granted access to EUE. Line with square denotes only HBSs access. Line with diamond denotes only MBS access

A. Multi-floor Building

As shown in Fig. 5, when P_{femto} equals 0.2 and building distance is 100m, the outage rate of emergency service is kept under 10% since the multi-floor building is within the service coverage area of MBS. As P_{femto} increases, the outage rate is efficiently reduced and eventually under 1% when P_{femto} is 0.8. In the building at cell edge, the emergency service requirement can be fulfilled under 5% outage rate when P_{femto} exceeds 0.5. Because this emergency service is rather coverage limited, MBS can not compensate for the outage event at cell edge.

B. Terraced Building

Fig. 6 shows the corresponding result in terraced building as those in multi-floor building. It is worth noting that the performance gain contributed by femtocells decreases due to the fact that the average path loss between EUE and its serving femtocell is raised for 2 reasons.

First, in the case EUE and serving femtocell are in the same 2-floor house, both femtocell and EUE can be resided at any of the floors, which increases both distance dependent path loss and penetration loss. Second, when serving femtocell and EUE reside in different houses, the missing of upper and lower close neighbor reduces the possibility that femtocell is close enough to EUE. As a result, compared with the case in multi-floor building, the increasing amount in EUE outage rate is 1-2% when building distance is 100m and around 5-12% when building is at cell edge.

Fig. 7 summarizes EUE outage rate when different P_{femto} are given under the assumption of multi-floor and terraced building respectively. At low P_{femto}, EUE in multi-floor building suffers a densely populated UE environment in comparison with EUE in terraced houses and results in higher outage rates. As P_{femto} increases, the outage rate of EUE in multifloor building decreases much faster due to the facts that femtocell reduces average uplink interference from neighbors' and it is more probable that EUE have a serving femtocell nearby in a multi-floor building. It is also noted that the emergency service can be only fulfilled at cell edge when P_{femto} exceeds a threshold (for the emergency service at 95th percentile, P_{femto} 0.43 and 0.8 are needed respectively).

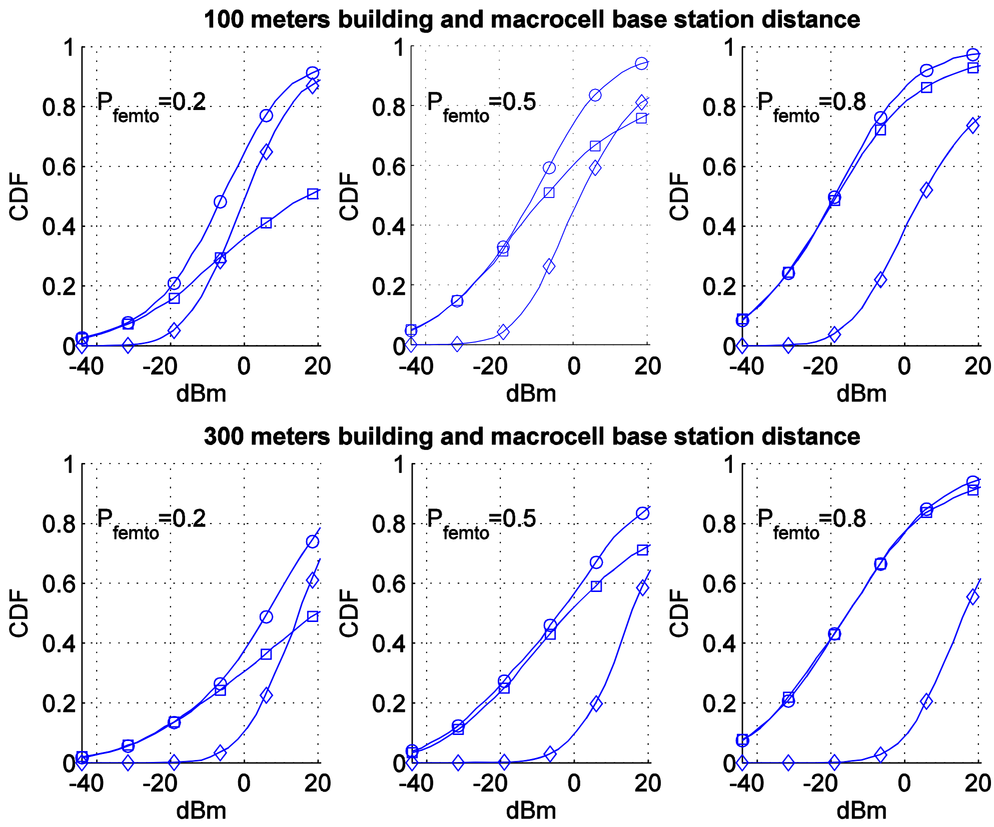

Fig. 6. CDFs of EUE transmission power in terraced houses. Line with circle denotes both MBS and HBSs are granted access to EUE. Line with square denotes only HBSs access. Line with diamond denotes only MBS access.

V. Conclusion and Future Work

In this paper we introduced a proposal for the exploitation of available femtocellular network resources in an emergency telemedicine scenario. The proposal has been supported by simulations based on an indoor environment in two types of MDU building structures. In both cases, the use of femtocells offered significant performance advantages in comparison to the conventional macrocellular network case, particularly for buildings located on the cell edge. In the future we intend to extend the study to consider the case of locations with detached single dwelling houses. Furthermore, we will further study performance of femtocellular approach for larger scale emergencies with multiple EUE units in the same location.

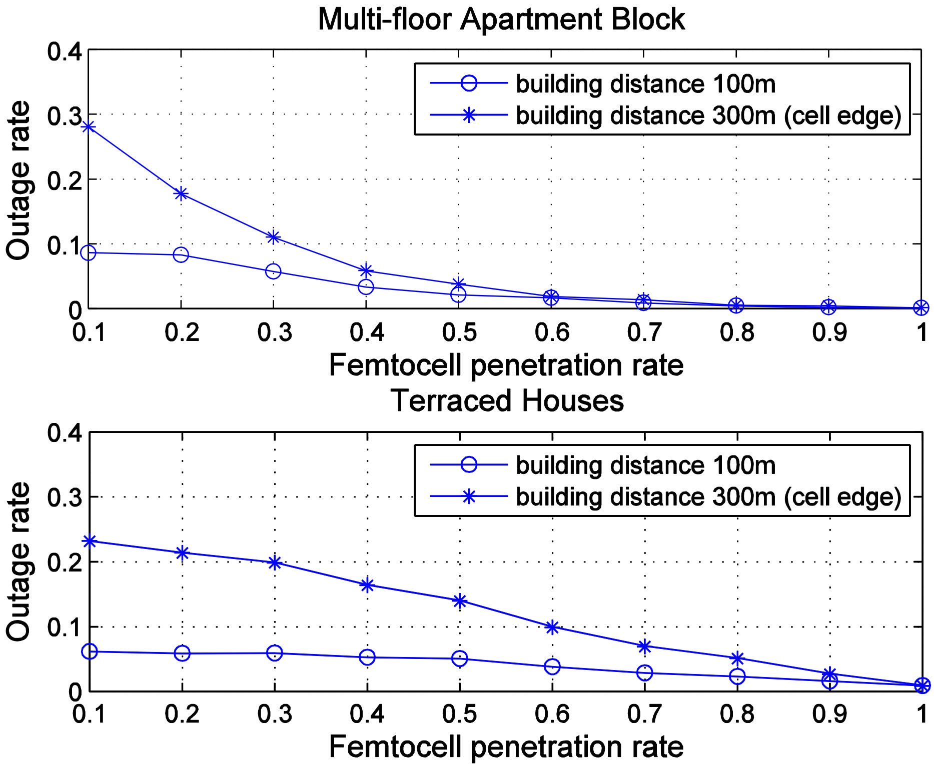

Fig. 7. Emergency service outage rate with different femtocell penetration ratios

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