

VoIP Transmission in Wi-Fi Networks with Partially-Overlapped Channels

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Abstract—The unprecedented cellular traffic growth caused by the ubiquitous mobile Internet access has motivated the search for solutions to cope with this explosive demand of connectivity. Mobile traffic offloading through Wi-Fi networks has emerged as an effective way of supplementing cellular services. This approach has been proven very effective to reduce the load of delay-tolerant traffic in cellular networks. Recent developments suggest that real-time traffic like VoIP could be also offloaded if Wi-Fi networks supported a reasonable number of concurrent calls. In this way, ubiquitous IEEE 802.11 networks operating in the 2.4 GHz ISM band could complement the cellular systems in indoor and rural environments. Wi-Fi networks are allocated 14 channels in this frequency band, thereof only 3 non-overlapped channels are allowed for Wi-Fi extended service sets in order to avoid interference. In this paper we investigate the use of assignment configurations with 4 partially-overlapped channels for VoIP transmissions, which may increase the network capacity in terms of concurrent users supported by Wi-Fi networks. Through computer simulations we demonstrate that 4-channel configurations are feasible at the expense of a tolerable degradation in quality of service for voice traffic with pedestrian mobility.

Index Terms—Cellular Systems, Traffic Offloading, VoIP, Wi-Fi

I. INTRODUCTION

IN RECENT years the ever increasing use of smartphones that offer ubiquitous Internet access, mobile social networking, and multimedia applications has led to a tremendous growth of mobile data traffic. It is forecasted that traffic originating from mobile devices will increase by a factor of 18 from 2011 to 2016 [1]. Cellular operators are already experiencing serious difficulties to handle these

unprecedented amounts of data over their network infrastructure, which was not originally planned and deployed for such a massive demand. In order to alleviate this problem, several traffic offloading solutions have been proposed [2], e.g., femtocells and mobile data offloading through Wi-Fi networks.

The *femtocell* technology consists of deploying small low-power cellular base stations (BSs) at home or other small indoor areas, backhauled to the cellular operator's core network by a regular fixed broadband access connection [3], e.g., asymmetric digital subscriber line (ADSL). The benefits from this solution are manifold [4], but since femtocells operate in the same licensed spectrum as overlay cellular networks, finding an available channel that is not already occupied is challenging. Some schemes that enable “intelligent” frequency reuse between macrocells and femtocells based on cognitive radio have been proposed [5], [6], but these solutions cannot be implemented without the use of efficient reconfigurable radio platforms.

Because of the severe shortage of radio resources for cellular networks in densely populated urban areas, the possibility of offloading part of the cellular traffic through Wi-Fi access points (APs) has been considered [7]–[10]. Wi-Fi networks operate in unlicensed frequency bands, e.g., the 2.4 GHz industrial, scientific, medical (ISM) band. Hence, unlike femtocells, Wi-Fi systems do not interfere with overlaying cellular networks. Generally, Wi-Fi APs are ubiquitously deployed in urban areas by commercial Internet providers or by private users in residential zones. Although Wi-Fi throughput is sometimes lower (depending on the number of users connected to the AP) and loss rates are higher, several large operators in the United States and Europe have already embraced Wi-Fi hotspots as a way of supplementing their cellular network services. Mobile traffic offloading has been proven highly effective for delay-tolerant applications. Two categories of mobile traffic offloading have been considered: *on-the-spot* and *delayed* [8]. On-the-spot traffic offloading consists of giving priority to Wi-Fi over cellular interfaces for data transmission on the spot. When the user moves out of the Wi-Fi zone then the unfinished data transfer is completed through the cellular network. A smartphone equipped with this application can initiate voice calls over Wi-Fi networks by default and switch automatically to the cellular infrastructure when deemed necessary. The second category consists of delaying mobile cellular data transfers until the user enters a

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Wi-Fi zone for offloading. If the waiting time exceeds the application's delay tolerance, then the traffic is transmitted over the cellular network. The achieved reduction of cellular traffic depends on the application's delay tolerance. Reduction of 45% of 3G traffic for a delay tolerance of 60 seconds was measured with a vehicular testbed in [7]. Contrastingly, simulations in [9] indicated that Wi-Fi already offloads 65% of the total mobile data traffic without using any delayed transmission. This observation suggests that Wi-Fi networks can also be an effective alternative for offloading mobile real-time data such as voice over Internet protocol (VoIP). Nevertheless, the capacity of Wi-Fi networks in terms of concurrent users is limited in the 2.4 GHz ISM band because of the requirement of using non-overlapped (orthogonal) radio channels to prevent the adverse effects of adjacent channel interference (ACI). In both urban and rural areas, there are a good number of underexploited indoor APs in the unlicensed 2.4 GHz ISM that can be good alternatives for cellular traffic offloading if the capacity of those Wi-Fi networks could be increased.

Therefore, in this paper we investigate the use of partially-overlapped channels in the 2.4 GHz ISM band for the transmission of VoIP traffic. The motivation for our work is the fact that more available channels in the 2.4 GHz will result in higher capacity for the offloading of cellular voice traffic through Wi-Fi networks. Our computer simulations demonstrated that the effects of ACI on the quality of VoIP transmissions in Wi-Fi networks arranged in a multicell layout with 4 partially-overlapped channels are negligible. These results may contribute to the enhancement of mobile voice traffic offloading, thereby alleviating the congestion of the cellular network infrastructure in densely populated urban areas or alternatively help to extend the cellular services to indoor areas and underdeveloped rural zones.

II. WI-FI CHANNELS IN THE 2.4 GHz ISM BAND

The set of IEEE 802.11 physical layer (PHY) standards utilize 14 overlapping channels in the 2.4 GHz ISM band as shown in Fig. 1. Only 11 channels are available in the United States and 13 in most European countries, whereas all the 14 channels are used in Japan. As recommended by the different 802.11 standards, channel assignment configurations with 3 non-overlapped channels should be used for collocated APs to prevent ACI. For instance, channels 1, 6, 11 in the United States and 1, 7, 13 in Europe are recommended 3-channel configurations. As hinted before, this restriction on channel utilization causes spectrum scarcity, especially in Wi-Fi networks with a large number of users. As a consequence, the Wi-Fi network capacity in terms of concurrent users is limited. In order to improve the spectrum utilization and increase the capacity, assignment configurations with 4 partially-overlapped channels, e.g., 1, 4, 8, 11 in the United States (1, 5, 9, 13 in Europe), have been proposed [11], [12]. Although some degradation in the quality of service (QoS) can be expected with these channel configurations, theoretical analyses have supported the idea of using 4 partially-overlapped channels for best-effort traffic, e.g., web browsing

[11], [13]. Basic experimental results [14] showed some throughput degradation for best-effort data transmission with a 4-channel configuration whereas subsequent experiments in a simple testbed demonstrated the contrary [12]. VoIP traffic, however, has different QoS requirements and the question of whether ACI in a 4-channel configuration significantly degrades real-time voice transmissions remained open.

We set out to investigate through computer simulations the feasibility of using 4-channel configurations for IEEE 802.11 networks with VoIP traffic. For this purpose a simulator of a basic service set (BSS), i.e., a communication link between an AP and a user's terminal (UT) was implemented. The performance of the BSS as part of an extended service set (ESS), i.e., a multicell Wi-Fi network layout with both 3- and 4-channel configurations was assessed. In order to obtain the worst-case scenario we simulated the PHY of the IEEE 802.11b standard. Since 802.11g and 802.11n operate with improved modulation schemes, their performance under the same ACI conditions in the 2.4 GHz ISM band is expected to be superior to that of 802.11b systems. Only VoIP traffic was considered for our simulations.

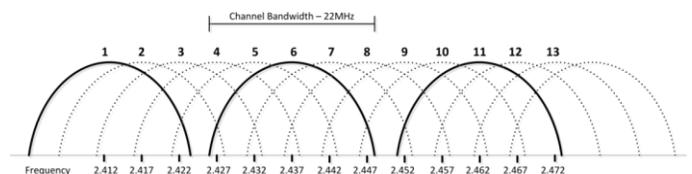


Fig. 1. IEEE 802.11 channels in the 2.4 GHz ISM band, where the center frequency of each channel is given in GHz. The additional 14 channel is centered at 2.484 GHz.

III. BASIC SERVICE SET SIMULATION

The performance of VoIP is generally measured in terms of user-perceived quality over a speech period comprising a number of VoIP packets. The so-called E-model provides an effective way to evaluate speech quality based on this subjective perception [15]. With the appropriate mathematical manipulation, this model translates a particular value of mean opinion score (MOS) into packet error rate (PER) on a communication link. According to the graphic of MOS versus PER in [16], the minimal acceptable QoS in a Wi-Fi network with VoIP traffic ensuring full user satisfaction is achieved with $MOS = 4$, which corresponds to $PER \leq 0.125$. The bit error rate (BER) threshold needed for a communication link with VoIP traffic can be calculated assuming that bit errors are mutually independent and uniformly distributed, thus

$$PER = 1 - (1 - BER)^N \quad (1)$$

where N is the number of bits in a packet. For $PER = 0.125$ and packet size of 1024 bytes, a maximal $BER = 1.6 \times 10^{-5}$ can be tolerated.

A. The Transmitter

First, we simulated the IEEE 802.11b PHY in the SimulinkTM platform. The transmitter (TX) was implemented with a voice encoder (VoCODER), which consisted of a file in waveform audio (WAV) format containing uncompressed

phone conversation recordings. A pulse code modulation (PCM) G.711 codec (μ -law for the United States and A-law for Europe) converted the file into a stream of bits. These data, referred to as physical layer service data unit (PSDU), undergo a framing process in which the physical layer convergence protocol (PLCP) preamble and header are added. The resulting PLCP protocol data unit (PPDU) goes to the modulation and spreading blocks as depicted in Fig. 2. The voice traffic is fed to the PHY as a continuous stream of packets. The network operates using the distributed coordination function (DCF) protocol for medium access control (MAC), but the request-to-send/clear-to-send (RTS/CTS) mechanisms were disabled in order to simulate a worst-case scenario in which interfering signals were always present. Simulating the RTS/CTS mechanism would create many silent periods during interframe spaces, which means less interference.

B. The Radio Propagation Channel

The BSS was assumed to be located in an indoor dispersive propagation environment, being the distance between AP and UT equal to 30 m. Three different propagation paths were assumed with time delay equal to 110 ps, 225 ps, and 325 ps, respectively. The path loss, L , was computed as [17], [18]

$$L = \begin{cases} 40 + 20\log(d) & d \leq 5 \text{ m} \\ 40 + 14 + 10\gamma \log\left(\frac{d}{5}\right) & d > 5 \text{ m} \end{cases} \quad (2)$$

where d is the propagation path between the AP and the MS and γ is the propagation coefficient after the break point. An empirical value of $\gamma = 4.5$ was chosen for the simulations. Additional 14 dB were considered for $d > 5$ m in order to take into account the signal attenuation by walls scattering in the same story. If the AP and MS are located in different stories, then the propagation loss has to be computed as [18]

$$L = 40 + 20\log d + nv + mw \quad (3)$$

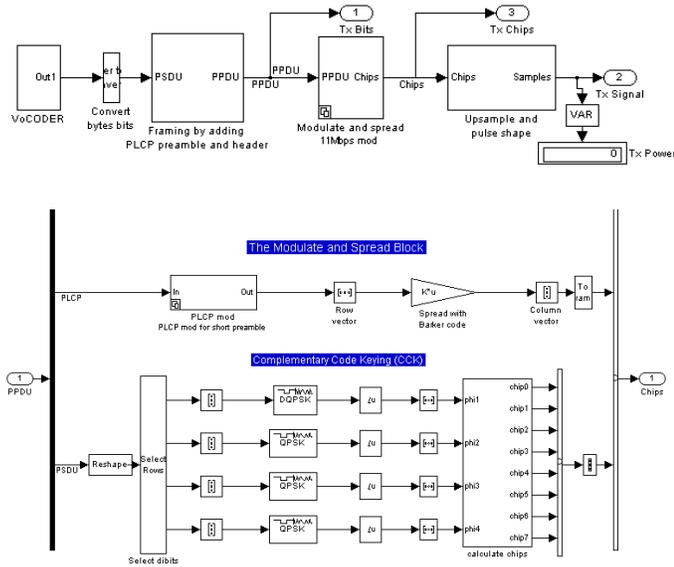


Fig. 2. The IEEE 802.11b TX simulator: VoCODER blocks (upper side), and modulation/spreading blocks (bottom).

where n and m are the number of floors and walls between antennas and v and w are attenuation factors for floor and wall in dB, respectively. Typical values for v and w can be found in [18]. However, multistory scenarios were not considered and we assumed that the BSS was located in a single-story building, which is again a worst-case scenario assumption.

C. The Receiver

The receiver (RX) was implemented with a filtering block for the received signal followed by a synchronization block. Next to these blocks were two delay blocks, demodulation and despreading and finally a de-framing block, which forms back a PSDU as shown in Fig. 3. The de-framing and despreading blocks produced a data bit stream that was compared to the original one by a block of BER meters, which estimated the errors in three different parts of the frame: preamble, header, and data. By summing them up, the total BER was calculated and depicted in a BER versus signal-to-noise ratio (SNR) graphic. In this case, the isolated BSS was exposed to the effects of channel fading, indoor path loss, and thermal noise at the RX, but no interference was present.

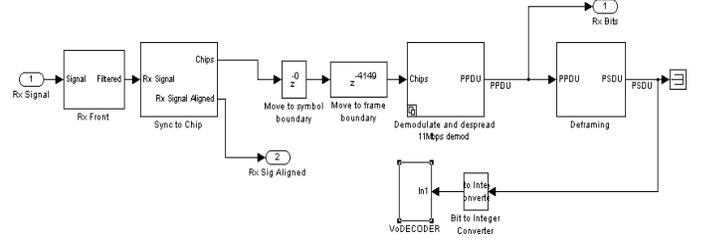


Fig. 3. The IEEE 802.11b RX simulator.

IV. EXTENDED SERVICE SET SIMULATION

Next, the BSS simulator with VoIP traffic was immersed in an ESS layout with both cochannel interference (CCI) and ACI coming from two tiers of surrounding cells. The AP of the BSS simulator was located at the center of the central cell, which was 30 m in radius. The AP was tuned to the frequency of the corresponding channel for each scenario as depicted in Fig. 4. Both 3- and 4-channel assignment configurations for the European and United States cases were considered.

Only the downlink traffic flow was analyzed in the BSS. Since more computational capabilities are available at the AP for error correction, the effects of interference on incoming traffic at the UT were more critical. In order to simulate the interference sources correctly, one UT in each cell was generated, which communicated with the corresponding AP in both directions (uplink and downlink). The location of each UT was selected randomly, and when the current phone call ended a new location was chosen for a new call. Thus, both surrounding APs and UTs contributed interference to the victim RX in the BSS. The transmissions of voice packets between cells were phased randomly, i.e., they were not synchronized or dictated by any MAC mechanism. This is a reasonable assumption because voice transmissions in other cells can be simply seen as interference sources.

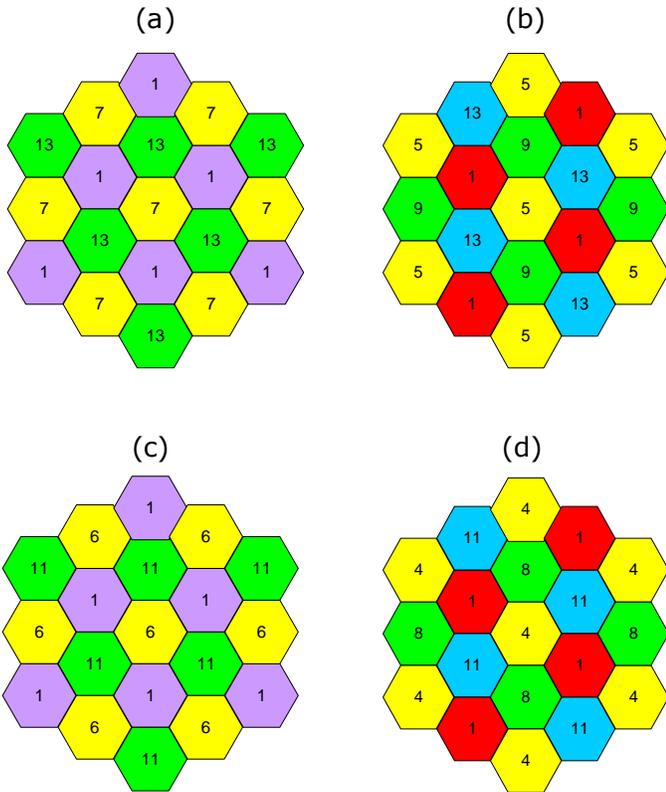


Fig. 4. Multicell IEEE 802.11b network layouts: (a) European 3-channel, (b) European 4-channel, (c) United States 3-channel, and (d) United States 4-channel configurations.

A. European Scenario

First, the transmission of VoIP packets over the ESS layout in Fig. 4(a) was simulated. The BSS was tuned to channel 7 and the obtained graphic of BER versus SNR is depicted in Fig. 5. For comparison, the BER of the isolated BSS is also shown. Notice that an increase of approximately 15 dB in SNR was necessary to ensure the same QoS of an isolated BSS link when the outer rings of interfering cells were added. The effects of ACI were calculated using the channel overlap factors presented in [8]. Next, the BSS was immersed in the 4-channel configuration ESS layout in Fig. 4(b) and tuned to channel 5. The graphic of BER versus SNR for the transmission of VoIP packets over the BSS in this case is also shown in Fig. 5. As seen, the QoS degradation in comparison to the 3-channel configuration is hardly distinguishable.

B. United States Scenario

As in the European case, the transmission of VoIP packets over the 3-channel configuration network layout in Fig. 4(c) was simulated. The BSS was tuned to channel 6 in this case. Figure 6 depicts the resulting graphic of BER versus SNR. The 4-channel configuration in Fig. 4(d) was also simulated with the BSS tuned to channel 4. The obtained graphics of BER versus SNR with both channel configurations were compared and 2 dB of QoS degradation were observed for the 4-channel configuration at $\text{BER} = 1.6 \times 10^{-5}$. This result is not surprising because in this scenario there was smaller spectrum separation (3 channels only) between two adjacent operational frequencies, contrasting with 4 channels of separation in the European scenario (see Fig. 1).

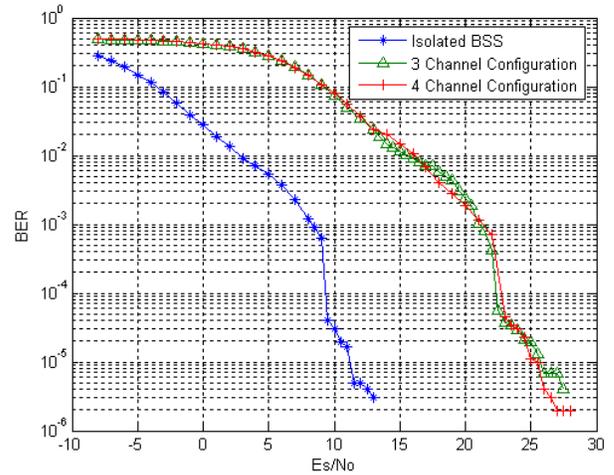


Fig. 5. BER versus SNR of VoIP transmission over a BSS immersed in both 3-channel and 4-channel configuration multicell Wi-Fi layouts (European scenario).

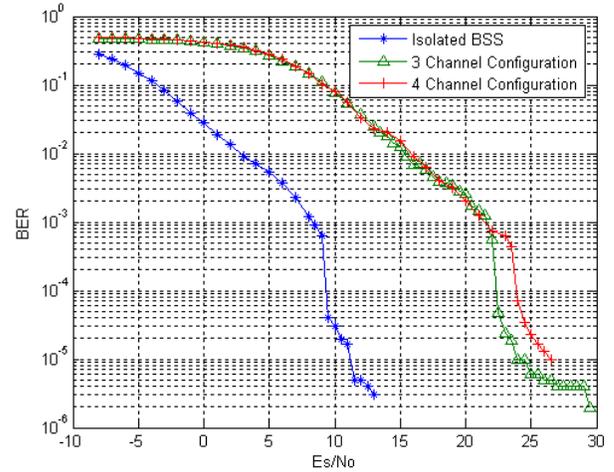


Fig. 6. BER versus SNR of VoIP transmission over a BSS immersed in both 3-channel and 4-channel configuration multicell Wi-Fi layouts (United States scenario).

C. Discussion

These computer simulations demonstrated the feasibility of using 4-channel configurations for Wi-Fi ESSs with VoIP traffic at least for the European case. In a subjective test based on human inspection, twenty volunteers were asked to listen to the WAV files at the exit of the UT; reportedly, no difference in audio fidelity between the 3- and 4-channel configurations was perceived. This matched the predictions of the E-model. A QoS degradation of approximately 1 dB is perfectly tolerable and using 4-channel configurations can increase the network capacity in terms of concurrent calls.

On the other hand, the QoS degradation of approximately 2 dB for the United States case was perceived as a slight loss in sound fidelity by 70% of the volunteers. Improving the value of SNR in order to compensate for the 2 dB of degradation can be attained by increasing the transmit power at the BSS, although this might lead to interference problems in the whole ESS network. Smart planning of the APs placement, especially in multistory environments, can create favorable conditions to implement 4-channel configurations in the

United States. Attenuation caused by radio propagation can reduce harmful interference between TXs operating at frequencies with spectral separation of 3 channels. A more extensive user-perceived quality assessment is required in order to evaluate the possibility of trading voice quality for network capacity.

D. Practical Considerations for Network Planning

Offloading cellular voice traffic through Wi-Fi networks is more complicated than delay-tolerant data. The main problem for the implementation of cellular traffic offloading is user mobility. As remarked in [7], the use of Wi-Fi networks from moving vehicles is challenging because of the short range of APs, which generally are not deployed to provide road coverage. Even if APs are in range, the link quality might not guarantee the proper transmission of all the mobile data traffic. However, in the case of delay-tolerant traffic the data can be stored temporarily until a better Wi-Fi connection is found to complete the transmission. This cannot be done with VoIP data. The so-called *Wiffler* system [7] tried to tackle this problem in a vehicular testbed by quickly switching to 3G if Wi-Fi could not transmit the VoIP data within a small time window. In spite of this effort, it remains uncertain whether Wi-Fi can supplement 4G (and beyond) services with the ubiquity and reliability that subscribers with vehicular mobility expect.

The implementation of voice traffic offloading appears to be more feasible for big indoor environments where a considerable number of users with pedestrian mobility seek cellular connectivity for voice and data transmission. Examples of such scenarios are malls, airports, and hospitals, where large amounts of voice traffic are generated by users with relatively low mobility. In these cases the Wi-Fi network can be planned and deployed in an ESS layout using 4-channel configurations to increase the network capacity for VoIP data transmission (Fig. 4). In these coordinated environments, i.e., when the ESS is likely managed by one particular administrator, the network planner can apply conventional indoor network planning tools [19] to determine the optimal placement of APs and the channel assignment with 4 partially-overlapped channels. Most channel assignment planning tools for Wi-Fi networks are based on optimization theory, where assigning channels is commonly modeled as the classical graph coloring problem. This requires a finite pool of available channels, F , to compute the optimal solution. As mentioned before, the 802.11 standards recommend a pool of $F=3$. Our simulations have demonstrated that $F=4$ is perfectly possible for VoIP traffic at least for the European scenario. The network planner can verify, with the aid of indoor propagation simulation tools and measurements, the interference levels expected at each Wi-Fi cell in a 4-channel configuration layout to determine whether our proposed approach can be also applied to specific networks in the United States. Uncoordinated outdoor scenarios with similar traffic demand and mobility like university campuses and residential areas can also benefit from the 4-channel configuration approach. Nevertheless, planning of the optimal AP placement and channel assignment is more challenging. In this case, the cooperation of cellular network operators, Wi-Fi service providers, and users is necessary for effective channel

allocation using the 4-channel configuration for all the different APs in the Wi-Fi coverage area. Moreover, incentives must be offered to the owners of private APs to allow the use of their home network infrastructure; this includes allowing the setting of the most convenient frequency channel to implement the offloading of cellular VoIP traffic.

V. CONCLUSION

In this paper we have demonstrated that the deployment of indoor multicell Wi-Fi networks with 4 partially-overlapped channels is feasible for transmission of VoIP traffic. The levels of ACI resulting from this approach produce minimal degradation in the QoS of VoIP transmissions. Although in the United States case this degradation can be perceived as a slight loss in sound fidelity, the network planner can decide whether to trade QoS for network capacity in highly congested networks. In-depth user-perceived quality assessment of the 4-channel configuration approach shall be conducted in this case in order to ensure satisfaction of the mobile subscribers. We envisage the application of these Wi-Fi ESSs to complement cellular voice services in large indoor environments with pedestrian mobility. Offloading of other real-time applications like video streaming through Wi-Fi networks has to be investigated too.

Our future work aims to implement a testbed to demonstrate the proposed 4-channel configuration approach in a realistic large indoor scenario. The percentage of traffic reduction in cellular networks by the use of 4-channel configuration Wi-Fi ESSs will be quantified and the economical aspects of the implementation will then be evaluated. Since deploying more Wi-Fi APs has a significantly lower cost than cellular network upgrades, network operators may consider this alternative as a viable and cost-effective solution to enhance their coverage in indoor and rural areas.

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REFERENCES

- [1] Cisco. (2012, May, 30). *Cisco visual networking index: forecast and methodology 2011–2016* [Online]. Available: http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-481360.pdf
- [2] A. Aijaz, H. Aghvami, and M. Amani, “A survey on mobile data offloading: technical and business perspectives,” *IEEE Wireless Commun.*, vol. 20, no. 2, pp.104–112, Apr. 2013.
- [3] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, “Femtocell networks: a survey,” *IEEE Commun. Mag.*, vol. 46, no. 9, pp. 59–67, Sep. 2008.
- [4] Y. Haddad, and D. Porrat, “Femtocells: opportunities and challenges of the home cellular base station for the 3G,” in *Proc. of International Conference on Wireless Applications and Computing*, Algarve, Portugal, Jun. 17–19, 2009.

- [5] S.-M. Cheng, S.-Y. Lien, F.-S. Chu, and K.-C. Chen, "On exploiting cognitive radio to mitigate interference in macro/femto heterogeneous networks," *IEEE Wireless Commun.*, vol. 8, no.6, pp. 40–47, Jun. 2011.
- [6] L. Huang, G. Zhu, and X. Du, "Cognitive femtocell networks: an opportunistic spectrum access for future indoor wireless coverage," *IEEE Wireless Commun.*, vol. 20, no.2, Apr. 2013, pp. 44–51.
- [7] A. Balasubramanian, R. Mahajan, and A. Venkataramani, "Augmenting mobile 3G using WiFi," in *Proc. of the 8th International Conference on Mobile Systems, Applications, and Services (MobySis)*, San Francisco, CA, Jun. 15–18, 2010, pp. 209–222.
- [8] B. Han, P. Hui, and A. Srinivasan, "Mobile data offloading in metropolitan area networks," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 14, no. 4, pp. 28–30, Oct. 2010.
- [9] K. Lee, I. Rhee, J. Lee, Y. Yi, and S. Chong, "Mobile data offloading: how much can WiFi deliver?," in *Proc. of the 6th International Conference on Emerging Networking, Experiments and Technology (CoNEXT)*, Philadelphia, PA, Nov. 30–Dec. 3, 2010.
- [10] S. Dimatteo, P. Hui, B. Han, and V. O. K. Li, "Cellular traffic offloading through WiFi networks," in *Proc. of the IEEE 8th International Conference on Mobile Ad-Hoc and Sensor Systems (MASS)*, Valencia, Spain, Oct. 17–22, 2011, pp. 192–201.
- [11] M. Burton. (2003, January, 24). *Channel overlap calculations for 802.11b networks* [Online]. Available: <http://www.techonline.com/electrical-engineers/education-training/tech-papers/4134127/Channel-Overlap-Calculations-for-802-11b-Networks>
- [12] A. Mishra, E. Rozner, S. Banerjee, and W. Arbaugh, "Exploiting partially overlapping channels in wireless networks: turning a peril into an advantage," in *Proc. of the 5th ACM SIGCOMM Conference on Internet Measurement (IMC)*, Berkley, CA, Oct. 19–21, 2005, pp. 311–316.
- [13] A. Mishra, V. Shrivastava, S. Banerjee, and W. Arbaugh, "Partially overlapped channels not considered harmful," *ACM SIGMETRICS Performance Evaluation Review*, vol. 34, no. 1, pp. 63–74, Jun. 2006.
- [14] Cisco Systems. (2004). *Channel deployment issues for 2.4-GHz 802.11 WLANs* [Online]. Available : <http://www.cisco.com/en/US/docs/wireless/technology/channel/deployment/guide/Channel.pdf>
- [15] A. Passito, E. Mota, R. Aguiar, L. Carvalho, E. Moura, A. Briglia, and I. Biris, "Using an E-model implementation to evaluate speech quality in voice over 802.11b networks with VPN/IPSec," in *Proc. of the International Conference on Wireless Communications, Networking and Mobile Computing (WCNM)*, Wuhan, China, Sep. 23–26, 2005, vol. 2, pp. 1123–1127.
- [16] O. Awoniyi, and F. A. Tobagi, "Effect of fading on the performance of VoIP in IEEE 802.11a WLANs," in *Proc. IEEE International Conference on Communications (ICC)*, Paris, France, Jun. 20–24, 2004, vol. 6, pp. 3712–3717.
- [17] Sputnik. (2004, April). *RF propagation basics* [Online]. Available : http://www.sputnik.com/resources/support/deployment/rf_propagation_basics.pdf
- [18] J. Tamminen. (2002, November, 19). 2.4 GHz WLAN radio interface [Online]. Available: http://wikiaccess.cttc.es/images/4/48/2.4_GHz_WLAN_Radio.pdf
- [19] S. Chiochan, E. Hossain, and J. Diamond, "Channel assignment schemes for infrastructure-based 802.11 WLANs: a survey," *IEEE Commun. Surv. Tutor.*, vol. 12, no. 1, pp. 124–136, 2010.