Per-Node Throughput Enhancement in Wi-Fi DenseNets

Kyungseop Shin, Ieryung Park, Junhee Hong, Dongsoo Har, and Dong-Ho Cho

Kyungseop Shin, Ieryung Park, Dongsoo Har, and Dong-Ho Cho are with Korea Advanced Institute of Science and Technology.

Junhee Hong is with Gachon University.

ABSTRACT

Wi-Fi networks are widely deployed for provision of Internet-centric data services. Since the inception of the Wi-Fi network in 1997 with its technical specification rooted in the IEEE 802.11 standard, much progress for higher data throughput has been made. Currently popular IEEE 802.11n Wi-Fi network in 2.4/5 GHz can deliver 600 Mb/s over a 40 MHz channel, which works well for most types of Internet-centric data services, and a later version of a Wi-Fi network based on IEEE 802.11ac is able to transmit at about 7 Gb/s. A simple configuration of a Wi-Fi network consisting of an AP and multiple stations for bidirectional data transmission enables low-cost implementation. High data rate provided at low cost as well as the abundance of Wi-Fi-capable mobile stations recently led to dense deployment of Wi-Fi networks, particularly in residential areas, business offices, and indoor/outdoor hotspots. However, dense deployment of Wi-Fi networks (e.g., Wi-Fi DenseNets) causes significantly increased overall interference, and as a result a significantly lowered achievable data rate. Thus, it is sensible to consider technologies that can resolve or mitigate deteriorated throughput of Wi-Fi DenseNets. In this article, technologies to deal with throughput enhancement of Wi-Fi DenseNets are addressed from three different perspectives: exploiting cellular technology for data transmission, elevating spectral efficiency, and controlling overall interference levels. Evaluation of interference control for Wi-Fi DenseNets is carried out in this article, and it is found that significant per-node throughput enhancement can be achieved.

INTRODUCTION

A typical Wi-Fi network consists of an access point (AP) and nodes (or stations, STAs) wirelessly connected to the AP. An AP and its associated nodes are called a basic service set (BSS). STAs such as smart phones, laptops, and smart pads can take on the role of AP to other STAs, establishing peer-to-peer (p2p) links between STAs in ad hoc mode [1]. This changeable configuration of a Wi-Fi network provides great flexibility in delivering different types of data services between APs and nodes or between nodes. Diverse applications requiring high data rate and abundant mobile STAs need more APs to attain concurrent data transmissions. With the typical service range of an AP covering tens of meters, Wi-Fi networks with respective APs are subject to dense deployments, particularly in airports, train stations, sports stadiums, apartments, and other hotspots. However, tens or hundreds of STAs within a small space of dense Wi-Fi networks, requesting diverse types of data services simultaneously, incur data collisions. Dense deployment of Wi-Fi networks naturally increases interference levels, so per-node throughput (or area throughput) of Wi-Fi DenseNets existing in such circumstances would be significantly decreased.

Recently, Qualcomm Inc. and Huawei Technologies Co. Ltd. announced the introduction of Long Term Evolution-Advanced (LTE-A) technology to the unlicensed frequency band (LTE-U) around 5 GHz [2]. The main goal of LTE-U is to offload explosively growing cellular traffic to the comparatively inactive unlicensed frequency band. Ironically, it is also conceived that data traffic of Wi-Fi DenseNets can be offloaded to cellular networks to get less dense operating conditions for Wi-Fi DenseNets [3].

Elevation of spectral efficiency is another option to mitigate the harsh operating conditions of Wi-Fi DenseNets. Current attempts to increase the spectral efficiency of 4G cellular networks [4] based on orthogonal frequency-division multiplexing (OFDM) can be adopted for Wi-Fi DenseNets. New technologies being considered for 5G cellular networks include non-orthogonal multiple access (NOMA) [5], spectrally efficient frequency-division multiplexing (SE-FDM) [6], and orthogonal frequency-division multiple access with variable tone spaces (OFDMA-VTS) [7]. Basic principles of these technologies are explained later in this article.

To deal with the issue of Wi-Fi DenseNets, the High Efficiency WLAN Study Group (HEW SG) was formed in May 2013, and as an extension of their activity, effort on standardization of IEEE 802.11ax was initiated in May 2014. The goal of the Task Group on IEEE 802.11ax is to improve per-node throughput of Wi-Fi DenseNets in the presence of interfering sources. They have considered indoor and outdoor environments such as public hotspots, apartments, and picocell streets, where Wi-Fi DenseNets are actually deployed. In order to increase area

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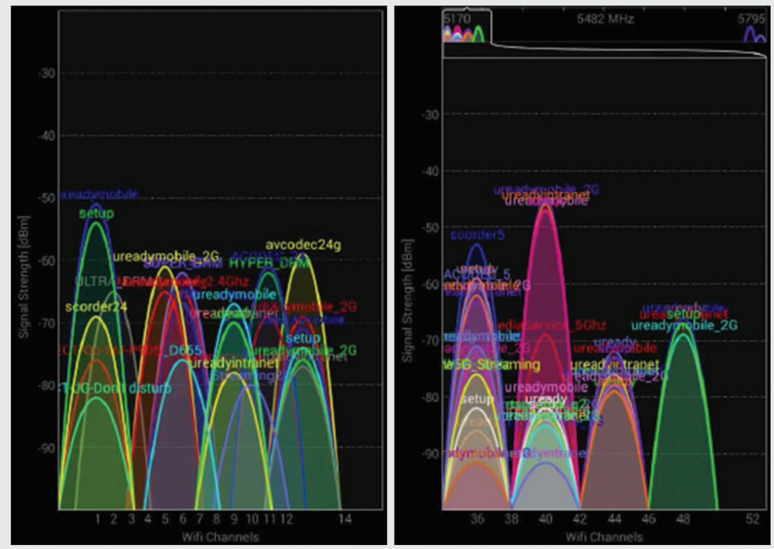
throughput of Wi-Fi DenseNets, they suggested dynamic sensitivity control (DSC) and transmit power control (TPC). The effect of DSC and TPC is evaluated, and the throughput gain from them is presented.

Technical evolution of Wi-Fi networks is described. Technologies to alleviate harsh operating conditions in Wi-Fi DenseNets and deployment scenarios devised by IEEE 802.11ax are also described. We present evaluation of DSC and TPC when applied to IEEE 802.11n DenseNets. We then briefly summarize this article.

Technical Review of Wi-Fi DenseNets

Figure 1 shows observed channel occupancy of IEEE 802.11n Wi-Fi networks in an indoor hotspot area of Suwon City, Korea. Figure 1a represents measured received signal strength indicator (RSSI) levels of Wi-Fi channels in 2.4 GHz band, and Fig. 1b illustrates measured RSSI level in 5 GHz band. Approximately 30 AP signals are observed in each frequency band, and each ID indicates an AP. For the majority of Wi-Fi channels, multiple APs coexist with similar RSSI levels, so associated AP and interfering APs cannot be judged by measured RSSI levels alone. It is seen in the figure that some Wi-Fi channels are overly crowded while other channels are not used at all. Uneven distribution of occupied Wi-Fi channels indicates that channels for APs are unfairly utilized. Wi-Fi DenseNets like this one can easily be found in other hotspots, and the number of detected APs even reaches 100 in some areas (e.g., the hotspot around Gangnam Subway Station in Seoul).



(a) (b)

Figure 1. Dense deployment of 802.11nWi-Fi networks in a hotspot (snapshot obtained by Wifi Analyzer®): a) deployment of 2.4 GHz Wi-Fi DenseNets; b) deployment of 5 GHz Wi-Fi DenseNets.

Evolution of Wi-Fi Networks

The IEEE 802.11 standard family comprises multiple versions of Wi-Fi standards [1]. Starting from IEEE 802.11, which supports up to 2 Mb/s, the data rate of Wi-Fi networks has consistently increased. Currently popular IEEE 802.11n Wi-Fi networks for 2.4/5 GHz provide data rate up to 600 Mb/s with 4 spatial streams of multiple-input multiple-output (MIMO) data transmission. The IEEE 802.11n standard is backward compatible with the IEEE 802.11a/b/g standards. For high throughput, the medium access control/physical (MAC/PHY) layers of IEEE 802.11n support multiple spatial streams and other key features: aggregation of acknowledgment frames, aggregation of data frames, and reduction of inter-frame spacing. Techniques for improving spectral efficiency in 5 GHz band are mostly concerned with IEEE 802.11ac [8], and spatial multiplexing to support multi-user (MU) MIMO has been implemented in its MAC/PHY protocols. IEEE 802.11ac provides dynamic frequency selection, dynamic session transfer, beamforming, high order modulation up to 256 quadrature amplitude modulation (QAM), and simultaneous transmission of data frames in different access categories (e.g., different traffic classes, such as video and audio, belonging to MUs). The key feature of the 802.11ad [9] in 60 GHz band is directional MAC protocol essentially utilizing beamforming technology to overcome excessive path loss due to the high frequency of the carrier signal. Standardization activity for the IEEE 802.11 standard family has mainly focused on the enhancement of the link throughput in a single BSS, and has not provided a complete solution for overlapped BSSs (OBSSs). However, in reality, due to the low-cost deployment of Wi-Fi networks, APs are indiscreetly deployed, often creating OBSSs with aggravated spectral efficiency.

Types of Wi-Fi DenseNet Deployment

In the real world, Wi-Fi DenseNets are observed in several different types of environments. The IEEE 802.11ax Task Group designed DenseNets scenarios for indoor dense residences, indoor business offices, and indoor small BSS hotspots/outdoor large BSS hotspots [10]. The main purpose of such practical scenarios is to set common environments where techniques for Wi-Fi DenseNets are adopted for benchmark testing to prove their spectral efficiencies and per-node throughputs. Evaluation of tested techniques for DenseNets is valid only with OBSS. Figure 2 depicts three different types of DenseNet deployments. The residential scenario in Fig. 2a involves interference between APs placed in apartment units. A multi-story building with story height of 3 m is considered, and 20 units of 10 m × 10 m are located on a single floor. There is one randomly located AP per unit, and each unit has N uniformly (randomly) distributed STAs. Figure 2b shows an indoor enterprise Wi-Fi network on a single floor in an office building. There are 8 offices, and each office is 20 m × 20 m. In each office, 64 cubicles of 2 m × 2 m coexist, and each cubicle possesses 4 randomly distributed STAs. Also, for each office, four APs are installed. A scenario for indoor small BSS hotspot /outdoor large BSS hotspot is illustrated in Fig. 2c with frequency reuse factor 1. In the outdoor large BSSs hotspot scenario, cell coverage is shaped in a hexagon, approximating isotropic channel property, with an AP at the center, and the distance between adjacent APs set to 130 m. The BSSs in Fig. 2c, with their APs placed by an enterprise, can be called an enterprise service set. Small cells delimited by circles indicate small BSSs with standalone APs or p2p links. The standalone AP is an AP that is not managed by the enterprise of the enterprise service set. In this scenario, interference between APs in an enterprise service set, interference between STAs of p2p links, and interference between APs belonging to different enterprise service sets are considered. The indoor small BSS hotspot scenario is very similar to the outdoor scenario with some exceptions, such as much shorter distance (12 m) between adjacent APs and neglect of interference between APs belonging to different enterprise service sets.

Technologies for Wi-Fi DenseNets

Here, technologies recently considered to resolve technical challenges in Wi-Fi DenseNets are addressed from three different perspectives: exploitation of cellular technology for data transmission, elevating spectral efficiency, and controlling overall interference level. Simultaneous transmission of LTE-U and Wi-Fi networks will mitigate traffic overload problems of 5 GHz frequency band where Wi-Fi networks are only utilized, and non-orthogonal multiple access schemes might be able to enhance spectral efficiency. DSC and TPC can be used effectively to reduce the overall interference level, which is converted to increased per-node throughput.

LTE-U — The incremental capacity of cellular networks cannot keep pace with the growth of cellular traffic. This situation motivates cellular operators to migrate some portion of cellular traffic to another frequency band. In order to take over some traffic in the cellular network, IEEE 802.11u [1] suggested the Wi-Fi passpoint, which enables handoff from a cellular network to a Wi-Fi network. However, seamless handoff cannot be achieved by a Wi-Fi passpoint alone. Therefore, demand for more systematic offloading has increased. Lately, Qualcomm Inc. and Huawei Technologies Co. Ltd reported LTE-U based on

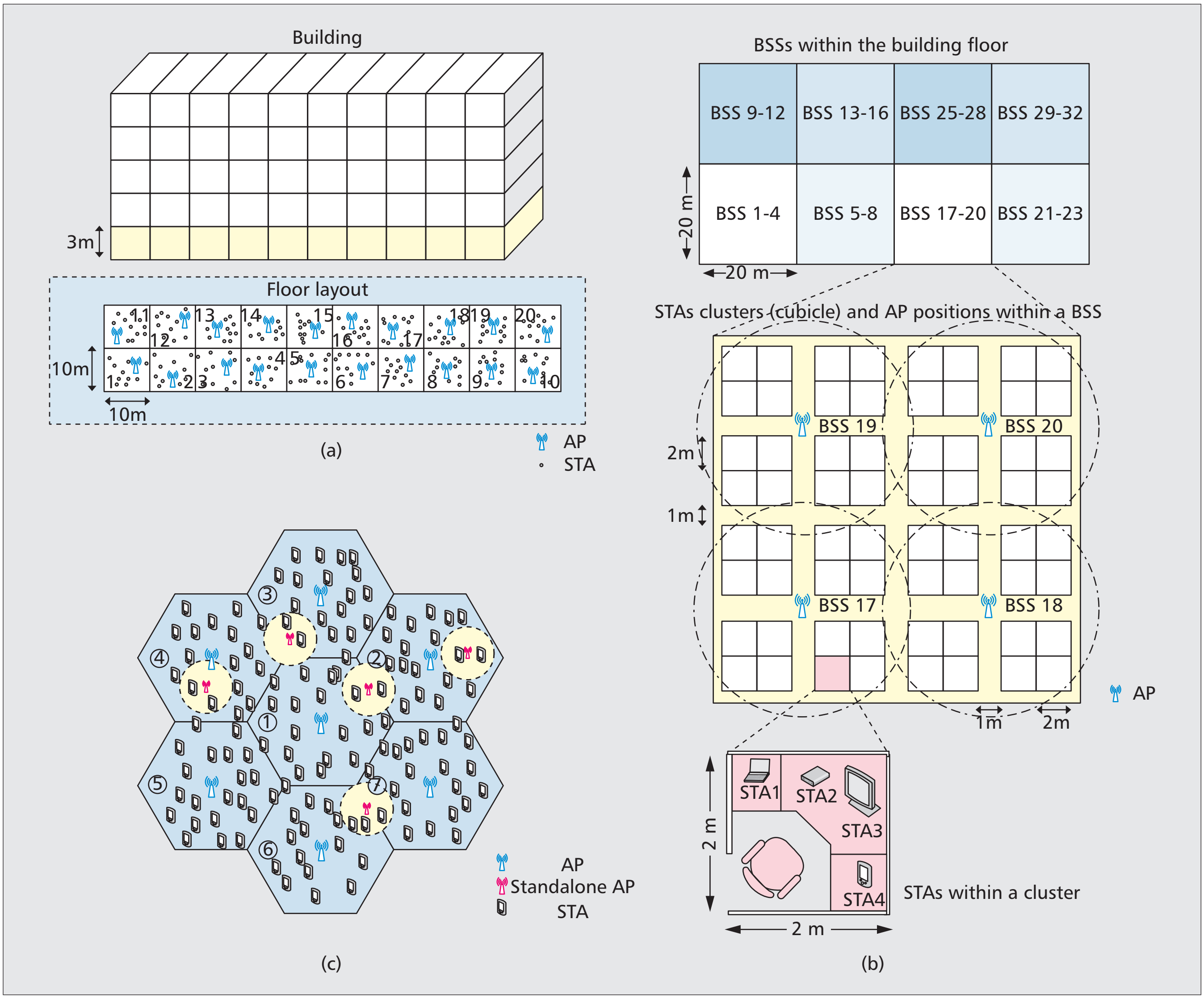


Figure 2. Deployment scenarios for Wi-Fi DenseNets: a) residential scenario; b) enterprise scenario; c) indoor/outdoor BSS hotspot scenario.

LTE-A. The main target of LTE-U is to alleviate large traffic of cellular networks by making use of unlicensed frequency band in 5 GHz. In Fig. 3, the aggregation of unlicensed carriers with licensed ones is illustrated. Both downlink and uplink are operated by LTE-A technology. For downlink transmission, carrier aggregation is performed to provide a higher data rate while a licensed carrier alone might be used for uplink transmission. Downlink transmission of data traffic is best effort type transmission, and in uplink, data transmission in unlicensed frequency band is allowed only when there is no significant interference detected or incurred during data transmission. Critical control frames for LTE-U are transmitted using licensed frequency band for both downlink and uplink. Unlicensed carriers are considered secondary carriers, and their operations are controlled by a cellular network. Joint scheduling between LTE-A and LTE-U is performed by the LTE-A cellular network. Currently, LTE-U and Wi-Fi networks are often discussed together for small cells and p2p communications.Cellular standardization activities to interwork with Wi-Fi networks have focused on handling traffic overflow of cellular network. In Third Generation Partnership Project (3GPP) standards, the interoperability (Releases 6 and 7), seamless handover and service reliability (Release 8 and 9), integrated access (release 10), and systematic interoperability of multiple radio access technologies (Release 13) between cellular and Wi-Fi networks are stated. The series of standardization efforts for interoperability between cellular and Wi-Fi networks enables smooth migration of data traffic from a cellular network to a Wi-Fi network, and vice versa. In the future, data traffic of Wi-Fi DenseNets can be handled in LTE-U to control the overall interference level of Wi-Fi DenseNets. Congestion of data traffic in unlicensed band for Wi-Fi devices might be resolved by simultaneous use of Wi-Fi and LTE-U technologies.

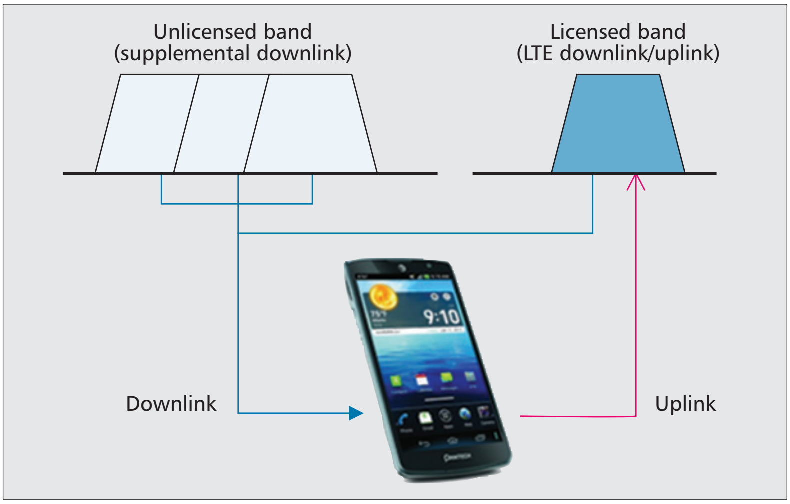


Figure 3. Downlink/uplink of LTE-U network exploiting unlicensed frequency band of Wi-Fi network.

Other Multiple Access Schemes: NOMA, SE-FDM, and OFDMA-VTS — For 5G cellular networks, non-orthogonal multiple access schemes to surpass the OFDM scheme in terms of spectral efficiency are under consideration. Most of these non-orthogonal multiple access schemes require higher system complexity and implementation cost than the OFDM scheme. However, it is expected that advanced signal processing and system-on-a-chip technology will help overcome these demerits. As non-orthogonal multiple access schemes, NOMA, SE-FDM, and OFDMA-VTS are explained.

The NOMA scheme in Fig. 4b exploits superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver. In downlink, if a station STA1 is located closer to an AP than other station STA2, the AP allocates more power to STA2 with power level P2, compared to STA1 with smaller power level P1. The signals transmitted from the AP are superposed, as seen in Fig. 4b, in the power domain over the same carrier. With more transmitting power for STA2, STA2 can decode its signal directly, treating the signal for STA1 as interference. On the other hand, STA1 decodes its signal in an iterative (successive) process. STA1 first decodes the signal for STA2, and reconstructs the signal for STA2 from decoded bits. The reconstructed signal is subtracted (cancelled) from the superposed signal, and the residual signal is decoded for STA1.This successive cancellation of interference for an STA can be extended for MUs. Provided that the NOMA scheme is adopted for OFDM, multiplexing gain over the power domain can bring improved spectral efficiency for OFDM systems.

The SE-FDM scheme in Fig. 4c uses tone spacing smaller than the tone spacing of the OFDM scheme (i.e. $\Delta f_S < \Delta f_O$). Decreased tone spacing with fixed total bandwidth indicates correspondingly increased spectral efficiency. The increased spectral efficiency of the SE-FDM is obtained at the cost of intentionally violated subcarrier orthogonality. The violated subcarrier orthogonality inevitably introduces interchannel interference (ICI), so the impact of the ICI must be reduced for successful decoding. To this end, high-complexity data decoding methods such as maximum likelihood detection and Gram-Schmidt orthogonalization are required.

The OFDMA-VTS scheme is based on variable tone spacing, as shown in Fig. 4d, so $\Delta f_1 \neq \Delta f_2$. Since the carrier frequency and mobility of each user are different, user-specific delay and Doppler frequency shift will be experienced by user subchannels. This leads to each user having unequal intersymbol interference (ISI) and ICI. Therefore, fixed tone spacing like OFDMA is inefficient for these user-specific subchannels, and results in cell capacity degradation. In OFDMA-VTS, the tone spacing for each subchannel is adjusted according to minimization of the composite interference (e.g., ISI plus ICI). Optimized tone spacing can provide increased spectral efficiency.

IEEE 802.11ax — Standardization activity of the IEEE 802.11ax Task Group, concerned with densely deployed WLANs, began in May 2014. Approaches appeared in the submissions of the HEW SG to enhance node throughput in DenseNets can be described as follows.

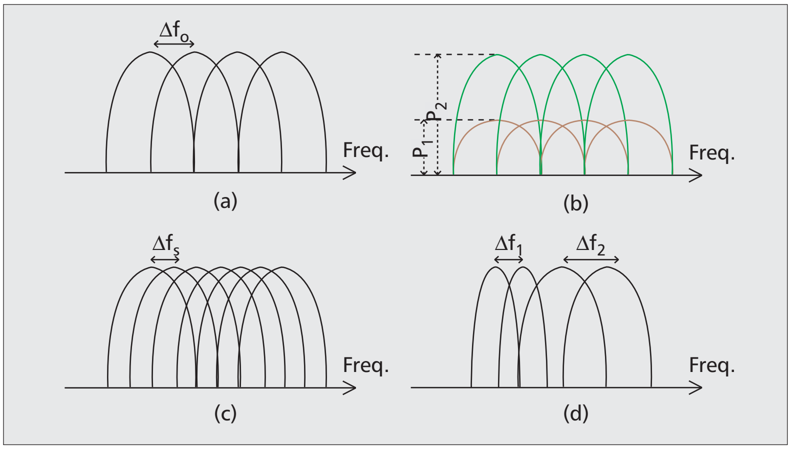


Figure 4. OFDM scheme and non-orthogonal multiple access schemes: a) OFDM; b) NOMA; c) SE-FDM; d) OFDMA-VTS.

"Possible Approaches for HEW" [11] deals with congestion, interference, and frame conflicts as three major problems in Wi-Fi DenseNets. The airtime of Wi-Fi DenseNets consists of frames, inter-frame space, and contention windows. Reduction of the control frames' overhead as well as aggregation of the data frames decreases the airtime of control frames. Congestion caused by excessive nodes taking up most of the airtime might be resolved by reducing the size of a control frame and increasing the relative size of a data frame. It is also mentioned that better quality of experience (QoE) can be obtained by limiting the number of associated STAs. Interference caused by dense deployment of Wi-Fi networks can be reduced by restricting the access of STAs located in the cell edge, which have comparatively low signal-to-interference-plus-noise ratio (SINR) and thus worse node throughput performance. Frame conflicts typically occur in hidden STAs and can be solved by modification of the channel access scheme and OBSS management.

"Enhancement on Resource Utilization in OBSS Environment" [12] suggests relaxed network allocation vector (NAV) protection to improve spatial reuse efficiency or per-node throughput. When an STA receives a request-to-send (RTS) or clear-to-send (CTS) signal, it sets NAV, which is a counter for how long the channel will be busy, and does not transmit any data. Thus, the STA does not attempt to transmit even if no CTS signal responding to the RTS is overheard. This would reduce spatial reuse efficiency. If the NAV is updated only when the CTS signal is overheard, STAs having data to transmit to other STAs can deliver data. From this viewpoint, relaxed NAV protection can increase spatial reuse efficiency.

Enhancing Per-Node Throughput in Wi-Fi DenseNets

In this section, enhancement of per-node throughput by the DSC and TPC is demonstrated, following the HEW SG scenarios. The main objective is to compare per-node throughputs of Wi-Fi DenseNets with and without interference control.

Per-Node Throughput Evaluation Condition

Clear channel assessment (CCA) is a channel sensing mechanism based on carrier sense and energy detection. The CCA sensitivity indicates a predefined threshold to judge the channel as busy or idle. The DSC dynamically changes the CCA sensitivity. Depending on the CCA sensitivity, the STA accesses the channel aggressively or passively. Benefits from the DSC can be explained in a couple of ways. When the interference level measured at an STA is close to the beacon signal level of an associated AP, the STA holds off data transmission to reduce overall interference. If there is a much lower interference level, the STA proceeds to transmit data to increase per-node throughput. TPC controls the transmit power at the transmitter to provide a predetermined power level at the receiver. Without TPC, the transmit power at the transmitter is fixed. When an STA is located close to the AP, the transmit power of the AP for the STA can be made small by leveraging small path loss of the link. This allows more STAs to establish p2p links within the BSS, and also provides a higher chance for APs and STAs in adjacent cells to reuse the same channel [13].

For the DSC, CCA sensitivity is set to (R-M) dBm, where R stands for the RSSI level of the beacon signal of the associated AP, and M represents a margin. M is set to 20 dB, which is a typical value for the margin. It is assumed that the channel characteristics over the time duration of the beacon signal transmission and data signal transmission by an AP are stationary. The TPC of the AP is adjusted to make the RSSI level of the receiving STA become –50 dBm, which is often considered a target RSSI level based on TPC [13]. For evaluation according to the scenarios in Fig. 2, downlink of IEEE 802.11n Wi-Fi networks is considered. The Tx power of AP is set to 18 dBm in a residential scenario, 21 dBm in an enterprise scenario, and 15 dBm in an indoor small BSS hotspot scenario [10]. The respective number of APs is 20 for residential, 32 for enterprise, and 7 for indoor small BSS hotspot. Each AP is equipped with four transmitting antennas, and each STA has two transceivers. Noise level is set to –101 dBm (= –174 dBm/Hz [thermal noise] × 20 MHz [channel bandwidth]), and SINR is evaluated for each STA.

Saturated payload for a given number of STAs is assumed, so the AP or transmitting STA of a p2p pair or standalone AP always has data to transmit. Also, collision-free scheduling, load balancing among STAs, and control overheads are considered. Other simulation parameters [10] include data frame size = 1472 bytes, aggregation level of data frames = 2, preamble duration = 40 μs, acknowledgement packet duration = 68 μs, RTS duration = 52 μs, CTS duration = 44 μs, SIFS duration = 16 μs, and expected waiting time for the channel acquisition by enhanced distributed channel access protocol = 100.5 μs. It is also noted that STAs do not act as APs for other STAs when they have connections to other APs.

Maximum achievable node throughput is obtained by Shannon's channel capacity formula for 4 × 2 MIMO systems. To get channel capacity by the formula, SINR is required. The interference level of SINR for an STA is evaluated over individual interfering APs, depending on their locations. Following the residential scenario, a single channel is used for all the APs. Categorization of interfering APs according to the number of penetrations of walls and locational proximity of each unit can be considered to simplify the computational process. If an STA in an apartment unit with ID = 3 in Fig. 2a, APs placed in adjacent units with ID = 2, 4, 13 and the other APs in remaining units are treated differently. For the APs in units with ID = 2, 4, 13, each of which shares a wall with the unit under consideration, combinations of STAs, one from each unit, are exhaustively taken into account. Let us assume that a composite interference level is obtained as $I_{adj} + I_{rem}$, where $I_{adj} = \Sigma I_a$, I_a = interference from an adjacent AP with index a, and $I_{rem} = \Sigma I_{na}$, I_{na} = interference from an AP with index na that does not belong to the set of adjacent APs. For every combination of nodes, the accumulated interference level is computed as I_{adj}. With the remaining units, the average interfering power of respective AP over STAs in each unit is computed and then added together over the remaining units to get I_{rem}. It is noteworthy that I_{rem} is used for all the STAs in the unit under consideration, whereas I_{adj} is evaluated for each different combination of STAs in adjacent units. With this composite interference level, the SINR and channel capacity of an STA are computed. Changing combinations of STAs in adjacent units, composite interference level and channel capacity are re-evaluated. Mean channel capacity obtained this way is assigned as node throughput. For other units such as that with ID = 11, only two adjacent units with ID = 1, 12 need to be considered for I_{adj}. From this process for STAs in units, per-node throughput is obtained. For the enterprise scenario, different channels are assigned for eight offices, so such categorization of interfering APs is not necessary. As depicted in Fig. 2b, four channels marked by distinct colors of offices are assigned, avoiding co-channel interference. Therefore, only three interfering APs and their associated STAs in the same office are considered as interference sources, neglecting co-channel interference because of distance. In the indoor BSSs hotspot scenario, all six interfering APs and their STAs are taken into consideration.

The IEEE 802.11n channel model [15] is adopted as the path loss model. Wall penetration loss is set to 12dB. Carrier frequency is 2.4 GHz with 20 MHz channel bandwidth. Evaluation of per-node throughput is performed by Matlab. Per-node throughput is acquired by averaging individual node throughputs of all the receiving nodes in a run, and the average per-node throughput in Fig. 5 with a 95 percent confidence interval is obtained over runs. The locations of APs in the residential scenario and STAs in all the scenarios are randomly updated in each run.

Results from DSC and TPC

Figure 5a shows the variation of per-node throughput according to the number of nodes without p2p pairs in an apartment unit(left side) and also according to the number of p2p pairs (right-hand side figure). Per-node throughput evaluation for p2p pairs is performed when the total number of nodes is 10 per apartment unit. Nodes for p2p pairs for p2p links are selected out of 10 nodes in each unit, and the remaining nodes are associated with an AP. It is noted that average per-node throughput is calculated for all the receiving nodes, including the receiving nodes of p2p pairs. With the DSC and TPC jointly used for downlink transmission, significant improvement of per-node throughput is obtained. The DSC enables an AP to get more transmission opportunities, since the nodes in the cell sense the channel as idle more frequently, and in addition to the presence of intervening walls that significantly reduce interference from other APs, the TPC is efficient in curtailing overall interference. Per-node throughput gain over the IEEE 802.11n networks without the DSC and the TPC is ranging from about 50 to approximately 100 percent, depending on the number of nodes.

Figure 5b demonstrates the variation of per-node throughput performance with increased number of nodes and p2p pairs per four cubicles, as depicted in Fig. 2b. The p2p pairs are selected out of 16 nodes. Since there is no wall between APs, the accumulated interference level due to adjacent APs is relatively large in comparison with the residential scenario, and as a consequence, gain of the per-node throughput by DSC and TPC is decreased in the enterprise scenario. This can be commonly observed in Figs. 5a and 5b with or without p2p pairs. Nevertheless, per-node throughput gain with or without p2p pairs is about 40 percent.

Figure 5c shows per-node throughput for indoor small BSSs hotspot scenario where seven BSSs coexist. Gain due to DSC and TPC is about 20 percent with a small number of nodes and increases up to 200 percent as the number of nodes increases. Compared to Fig. 5a, the effect of DSC and TPC in terms of gain is more profound with increased number of nodes or p2p pairs. This is partially due to the random locations of APs in a residential scenario, which can accentuate the adverse impact of some interfering APs close to the node under consideration. Less significant overlapping of cell coverage in the indoor small BSS hotspot scenario, compared to the significant overlapping of cell coverage in the enterprise scenario in Fig. 5b, seems to be beneficial to obtain the gain of DSC and TPC. The graph on the right side of Fig. 5c represents evaluation results according to the number of standalone APs when 30 nodes exist in each BSS. Each standalone AP is associated with two STAs. With standalone APs, gain over the IEEE 802.11n Wi-Fi network without DSC and TPC is greater than 100 percent. As a whole, gain from DSC and TPC for Wi-Fi DenseNets is significant for various types of deployments.

Conclusion

This article has focused on technologies suitable for Wi-Fi DenseNets. LTE-U has been considered as a candidate technology to offload data traffic of Wi-Fi DenseNets to cellular networks. Several non-orthogonal multiple access schemes

Clear channel assessment (CCA) is a channel sensing mechanism based on carrier sense and energy detection. The CCA sensitivity indicates a pre-defined threshold to judge the channel as busy or idle. The DSC dynamically changes the CCA sensitivity. Depending on the CCA sensitivity, the STA accesses the channel aggressively or passively.

for 5G cellular networks were addressed as potential approaches to increase spectral efficiency of Wi-Fi DenseNets. In general, enhancement of spectral efficiency is obtained at the cost of increased system complexity. Three different deployment scenarios suggested by the HEW SG have been applied to find out the benefits of interference-level control. An interference control scheme in the form of DSC and TPC, suggested by the HEW SG, has been tested with three different deployment scenarios. It has been found that control of CCA sensitivity and transmit power to reduce the overall interference level provides significant per-node throughput improvement to Wi-Fi DenseNets, regardless of deployment scenarios.

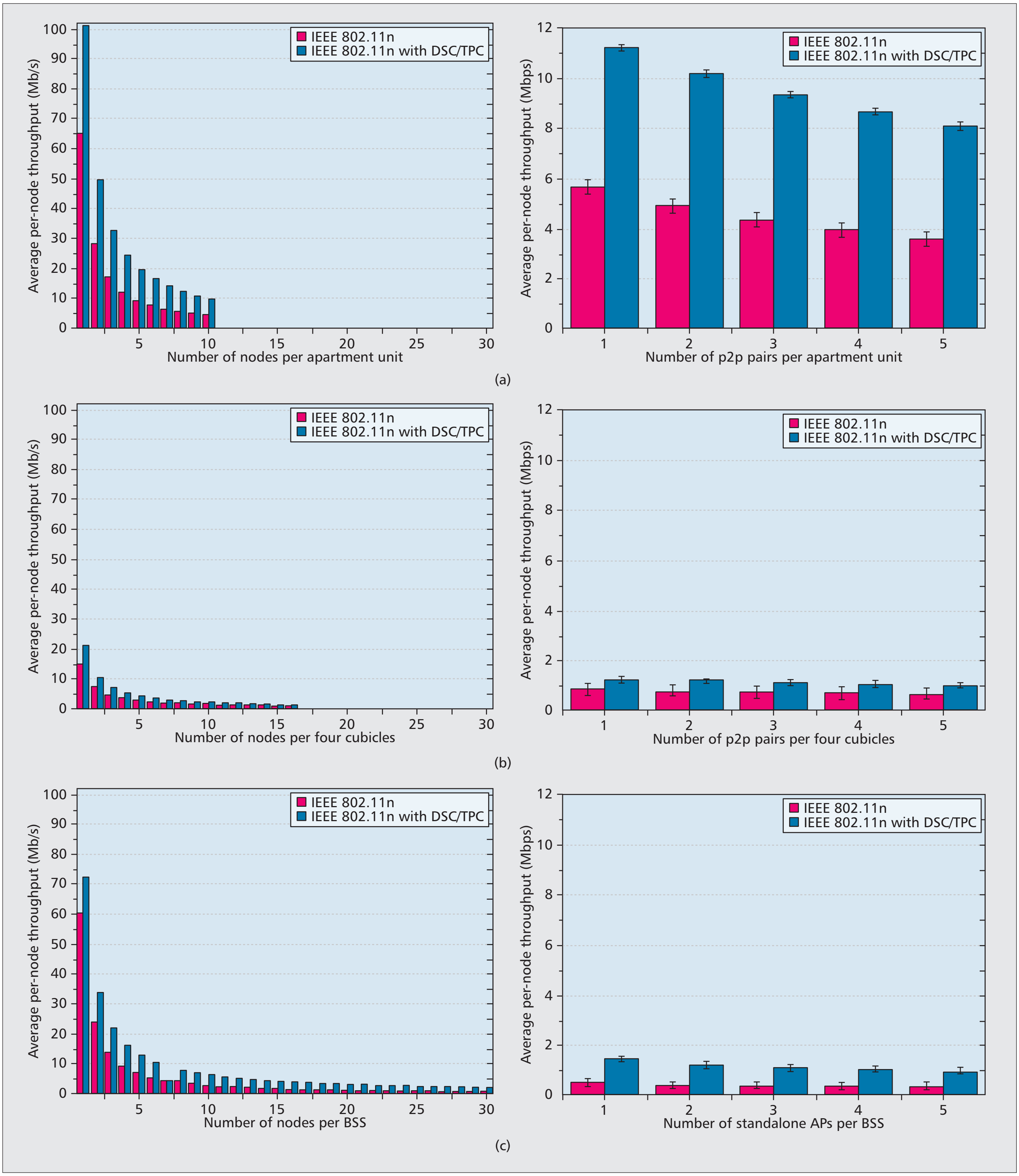


Figure 5. Evaluation results for Wi-Fi DenseNets according to the scenarios in Fig. 2: a) residential scenario; b) enterprise scenario; c) indoor BSSs hotspot scenario.

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REFERENCES

[1] IEEE 802.11-2012, "Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," Mar. 2012.

[2] "Extending the Benefits of LTE Advanced to Unlicensed Spectrum," QUALCOMM, Nov. 2013, http://www.qualcomm.com/media/documents/extending-benefits-lte-advanced-unlicensed-spectrum

[3] I. Hwang *et al.*, "A Holistic View on Hyper-Dense Heterogeneous and Small Cell Networks," *IEEE Commun. Mag.*, vol. 51, no. 6, June 2013, pp. 20–27.

[4] Y. Kishiyama *et al.*, "Future Steps of LTE-A: Evolution Toward Integration of Local Area and Wide Area Systems," *IEEE Wireless Commun. Mag.*, vol. 20, no. 1, Feb. 2013, pp. 12–18.

[5] NTT DOCOMO, "Requirements, Candidate Solutions & Technology Roadmap for LTE Rel-12 Onward," 3GPP RWS-120010, June 2012.

[6] I. Kanaras *et al.*, "Spectrally Efficient FDM Signals: Bandwidth Gain at the Expense of Receiver Complexity," *Proc. IEEE ICC*, June 2009, pp. 2701–3706.

[7] S. Lim *et al.*, "Optimal Tone Space Selection Scheme for OFDMA-VTS in Carrier Aggregation," *IEEE Trans. Wireless Commun.*, vol. 12, no. 11, Nov. 2013, pp. 5679–91.

[8] IEEE 802.11ac, http://www.ieee802.org/11/Reports/tgac_update.htm.

[9] IEEE 802.11ad, http://www.ieee802.org/11/Reports/tgad_update.htm.

[10] IEEE 802.11-14/0621r3, "Tgax Simulation Scenarios," Sept. 2014.

[11] IEEE 802.11-13/0758r0, "Possible Approaches for HEW," July 2013.

[12] IEEE 802.11-13/1056r1, "Enhancement on Resource Utilization in OBSS Environment," Sept. 2013.

[13] IEEE 802.11-13/1290r1, "Dynamic Sensitivity Control for HEW SG," Apr. 2014.

[14] IEEE 802.11-03/940r4, "TGn Channel Models," May 2004.

BIOGRAPHIES

KYUNGSEOP SHIN received his B.Sc. and M.Sc. degree from KAIST, Daejeon, Korea in 2009 and 2011. Now he is in the Ph.D. program under the supervision of Prof. Dong-Ho Cho. His current research interests are bioinformatics, and medium access protocol for ad hoc wireless communications and wireless local area networks.

IERYUNG PARK received his B.Sc. from Kyunghee University in 2007 and his M.Sc. degree from Gwangju Institute of Science and Technology in 2009. He has been involved with a variety of industrial projects on communication system design at Samsung and CoreLogic. Now he is in the Ph.D. program under the supervision of Prof. Dongsoo Har. His current research interests are machine-to-machine communications and wireless power transfer.

JUNHEE HONG received his B.Sc. degree in electrical engineering from Seoul National University, Korea, in 1989 and his Ph.D. degree in electrical engineering from Seoul National University in 1995. He has been a professor of electrical power engineering at Gachon University, Kyunggi-do, Korea, since 1995. His research interests include smart grid, super grid, renewable powered desalination, and their communication infrastructure.

DONGSOO HAR received his B.Sc. and M.Sc. degrees in electronics engineering from Seoul National University in 1986 and 1988, respectively. He received his Ph.D. degree in 1997 from Polytechnic University, Brooklyn, New York. He was awarded Best Paper Award (Jack Neubauer Award) from *IEEE Transactions on Vehicular Technology* in 2000. His microcell model (Har-Xia-Bertoni model) has been widely quoted for practical deployment of cellular networks. Since 2013 he has been a faculty member of KAIST.

DONG-HO CHO [M'85, SM'00] received a Ph.D. degree in electrical engineering from KAIST in 1985. Since 1998, he has been a professor in the Department of Electrical Engineering of KAIST. He has been a director of the KAIST Online Electric Vehicle Project since 2009 and has served as head of the Cho Chun Shik Graduate School for Green Transportation since 2010. His research interests include mobile communication, online electric vehicle systems based on wireless power transfer, and bioinformatics.

It has been found that control of CCA sensitivity and transmit power to reduce the overall interference level provides significant per-node throughput improvement to Wi-Fi DenseNets, regardless of deployment scenarios.