Performance Evaluation of DRPNext in ECMA-368 Wireless Personal Area Networks

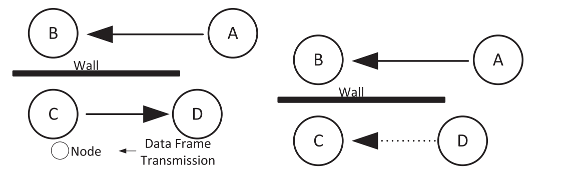
Holger Rosier, Christian Kukla, Jens H. Frerichs
Communication Networks (ComNets) Research Group, Faculty 6, RWTH Aachen University
Email: {hor, cka, jef}@comnets.rwth-aachen.de

***Abstract*—Wireless devices are broadly adopted to the digital home environment, not least through integration of radios to Consumer Electronics (CEs) like TV screens or portable multimedia equipment. Accompanied by growth in wireless devices, demand on data rate increases, imposing new challenges on Medium Access Control (MAC) to improve channel access efficiency. Ultra Wideband (UWB) ECMA-368 offers very high data rate for short range communication. Two MAC protocols are standardized, the random based Prioritized Contention Access (PCA) and the Distributed Reservation Protocol (DRP), which is known to gain efficient channel access without data frame collision even in densely populated wireless network scenarios. Radio frequency signals propagated in the wireless channel are distorted and attenuated from obstacles. Particularly in home environments furniture and walls lead to not completely meshed network scenarios, thus raising the impact from hidden and exposed nodes on system capacity. The achievable throughput from gaining channel access concerning DRP channel access is not affected in presence of hidden nodes, whilst exposed nodes in wireless network scenarios lower system capacity. This paper presents an improvement to DRP, called DRPNext, to mitigate exposed nodes impact on system capacity and shows system capacity gain by more than 30% in benefit from reduced channel reuse distance in home environments.**

***Index Terms*—DRP, distributed reservation protocol, wireless personal area networks, mac, ultra wideband, ECMA-368, exposed nodes, home environment, DRPNext**

I. Introduction

Numerous wireless communication systems operating in license-exempt frequency bands are available today, differing in communication range, power consumption and offered data rate. The great acceptance of wireless communication systems among users leads to densely populated network scenarios, where several wireless nodes exist in the network and, associated therewith, a growing competition for channel access permission on sparse channel resources. It makes an efficient MAC inevitable, in particular for high data rate services. The ECMA-368 UWB standard promises very high throughput of $1\ ^{\mathrm{GB}}\!/_{\mathrm{s}}$ with low power consumption for short range Wireless Personal Area Network (WPAN) communication. The UWB signal power emission is restricted to -41 $^{\mathrm{dBm}}\!/_{\mathrm{MHz}}$, makes frequency spectrum given to primary users in advance, available for license-exempt usage, adequate for services within the digital home environment, like high definition video and TV data transmission. The wireless channel of the home environment is recognized to be from challenging condition, where the radio frequency signal on its way from sending node to the receiving node is distorted in spite of small distances by furniture, walls and doors, leading to different nodes in the neighborhood seen by every node within the network. Such a network scenario is not completely meshed, meaning the connectivity is lower than one. Fig. 1(a) depicts the hidden node problem, where Node C uses a Modulation and Coding Scheme (MCS) for data frame transmission inadequate for peer Node D to successfully decode data frames, because the radio signal emitted by the third Node A raises insufficient Signal over Interference plus Noise Ratio (SINR) at Node D. An exposed node problem is shown in Fig. 1(b). Node D, having data frames ready to send, defers from gaining access to the channel, although, even the third Node A is currently transmitting data frames, a concurrent data frame transmission is possible. Occurrence of hidden and exposed nodes depend on misestimating interference power at the peer node position. The system throughput decreases in presence of hidden nodes, due to repeated data frame transmissions, whilst for exposed nodes a gain in system capacity is possible. As seen from Fig. 1, essential to recognize exposed and hidden nodes is the one and two hop neighborhood and whether neighbors are receiving or transmitting data frames. In this paper the DRP is extended to recognize exposed nodes by gathering information from one and two hop neighborhood and subsequently mitigate the impact on system capacity by gaining access to the channel for data frame transmission at the same time an exposed node is transmitting data frames. The improvement is called Distributed Reservation Protocol with Enhanced Neighborhood Evaluation and Exposed Node Mitigation (DRPNext). The paper is organized as follows: Related work is shown in Section II, Section III introduces the ECMA-368 standard, Section IV focuses on DRPNext, in Section V the UWB channel model is described, followed by an analytical study for interference calculation in UWB network scenarios in Section VI, Section VII shows results obtained from simulation and finally Section VIII concludes



(a) Hidden Node. (b) Exposed Node.

Fig. 1: Hidden and Exposed Nodes in a Simple Scenario.

the paper.

II. Related Work

Contribution on mitigation of exposed node impact on system capacity can be classified to approaches where transmission power is controlled on the PHY Layer or further management data frames are used on MAC Layer to synchronize user data frame transmission. Following from great popularity most research is on IEEE 802.11 WLAN technology. Reference [1] gives a comprehensive study on densely populated WLAN scenarios, emphasizing the impact of exposed nodes to system capacity. A node assumes itself to be exposed by broadcasting additional management data frames, to be standardized in IEEE 802.11, and subsequently gains channel access regardless of channel state. In the same way as [1], the work from [2] proposes management data frames to be broadcasted in the network. Exposed nodes are recognized from the one and two hop neighborhood information. Physical carrier sensing becomes obsolete, where an exposed node is assumed. Data frame transmission synchronization to the nearest neighbor and skipping carrier sensing seem to be disadvantageous in presence of a third transmitting node, which may cause harmful interference. The authors from [3] achieve a higher system capacity in ad hoc networks from synchronizing data frame transmission. Without new types of management data frames a node assumes to be exposed from RTS/CTS and MAC header frame reception, thus limits time duration where nodes transmit user data frames concurrently to payload transmission duration, critically assessed in scenarios where high data rates are used. Power control is addressed in [4], where nodes use reasonable transmit power for data frame transmission while increasing spatial reuse. However, in the work from [4] it ignores that exposed nodes depend on data frame transmission direction of a link [1], [5]. Gathering information on one and two hop neighborhood from management data frame transmission seems to be most promising. It is a challenging task in IEEE 802.11 networks where new types of management data frames are to be standardized, whilst in ECMA-368 this information is mandatory broadcasted by active nodes in Beacons and used, described in the following, to recognize exposed nodes and mitigate their impact on system capacity.

III. ECMA-368

The ECMA-368 standard [6] applies contention based as well as reservation based channel access. The contention based channel access called PCA is derived from IEEE 802.11 Enhanced Distributed Channel Access (EDCA) [7]. The reservation based channel access is called DRP and is based on the proposal in [8].

A. Physical Layer

ECMA-368 is a standard for UWB WPANs operating in the frequency range from 3.1 GHz to 10.6 GHz. The spectrum is subdivided into frequency bands with a bandwidth of 528 MHz each. Orthogonal Frequency Division Multiplex (OFDM) is

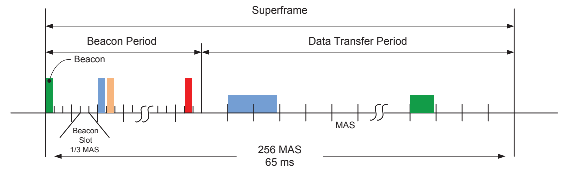


Fig. 2: The ECMA-368 Superframe.

applied with a symbol length of 312.5 ns. Data symbols are modulated onto 128 subcarriers by means of one out of eight MCSs providing data rates from 53.3 Mb/s to 480 Mb/s in the first version of the standard.

B. Medium Access Control Layer

Time is divided into Superframes (SFs) with a duration of 65 ms, as presented in Fig. 2. A SF comprises 256 Medium Access Slots (MASs), each with a duration of 256 μs. It is mandatory for each active node to send a short management frame, called Beacon, in the Beacon Period (BP). The maximum BP length limits the number of active nodes to 86. A Beacon carries Information Elements (IEs), giving information on capabilities of the node and channel reservations in the Data Transfer Period (DTP) of the SF. During the DTP nodes transmit user data frames in one or more reserved MASs.

1) Distributed Reservation Protocol (DRP): The DRP reserves channel time for transmission of data frames exclusively. The shortest radio resource unit which can be reserved is one MAS. ECMA-368 provides no guidelines how to reserve MASs. The amount of MASs required to be reserved per node depends on its offered traffic and has to be calculated by the node itself. In terms of ECMA-368 the source node is called reservation owner, the receiver node is called reservation target, owner and target for short. The owner proposes in its Beacon a certain MAS allocation pattern. If the proposed MASs are unoccupied in the view of the target, the target acknowledges the MAS allocation. The negotiation is done by exchanging the Distributed Reservation Protocol Information Elements (DRPIEs) carried in Beacons of owner and target. This two-way handshake inhibits transmissions confirming the reservation of hidden nodes. Information on current reservations of MASs are continuously repeated in each BP. Thus, nodes in mutual receive range of the owner and the target defer from trying to reserve the respective MASs and exclusive data frame transmission is guaranteed. Nodes in mutual receive range are members of an individual neighborhood called Beacon Group (BG). MAS reservations are respected in the BGs of owner and target, thus nodes defer from channel access if they are in mutual decoding range.

2) Information Elements (IEs): ECMA-368 standardizes several IEs for broadcasting management information, some of them are mandatorily included in each Beacon. In order to IEs nodes get aware of their neighborhood, they are informed on ongoing data frame transmission in the DTP and how nodes are related to each other, either owner or target of an established DRP link. The one and two hop neighborhood information used to recognize exposed nodes in DRPNext is gathered from:

- DRPIE: Nodes currently involved in DRP data frame transmission give information on reserved MASs and whether they are owner or target of a DRP data frame transmission.
- Beacon Period Occupancy Information Element (BPOIE): Nodes give information on received Beacons, from which node in which Beacon Slot a node has received a Beacon during the last BP.
- Distributed Reservation Protocol Availability Information Element (DRPAvail): Nodes announce preferred MASs for DRP data frame transmission.

IV. DRPNext

Gaining channel access from DRPNext requires extended neighborhood evaluation upon MAS reservation. A node gets aware of its one hop neighborhood through BPOIEs. Nodes in two hop neighborhood are detected from comparing the nodes own BPOIE to the received BPOIEs. Information on DRP MAS reservation is extracted from DRPIEs. In Fig. 3 Node A, called tagged node, tries to gain channel access from DRPNext to transmit data frames to Node B. Nodes C and G are owners of DRP links, called foreign owners, and transmit data frames to their targets Node D and Node F. Nodes B and D are one hop neighbors of Node A. This information is included in the BPOIE of Node A. Comparing the BPOIE of Node A to that of Node B discovers Nodes F and E to be in Node A's two hop neighborhood. Concerning standard DRP Nodes A and B grant channel access to Nodes G and C exclusively, as they are informed on data frame transmission by DRPIEs. DRPNext considers Node F to be exposed from Node A, as the foreign owner Node G is not in one hop neighborhood to Node B and the foreign target Node F is not in one hop neighborhood to Node A. Thus Node B proposes MASs reserved by Node G to be reusable for data frame transmission from Node A to Node B. This evaluation is done for every node within the BG. The owner of a DRP link considers the reusable marked MASs obtained by itself from neighborhood evaluation and from the proposed MAS through DRPAvail by its target for DRP MASs reservation. The algorithm for DRPNext is stated in Algorithm (1).

V. UWB Channel Model

To obtain accurate results from system performance evaluation, Non Line of Sight (NLOS) and Line of Sight (LOS) probabilities for channel condition are taken into account, as a detailed ground plan of a home environment with the arrangement of concrete walls, interior and furniture limits the obtained results to the specific scenario [9]. NLOS and LOS probabilities for the home environment UWB Channel Model (UCM) are shown in Fig. 4 [10], where $P(hardNLOS|NLOS)$ refers to the conditional probability of severely attenuated radio signals through concrete walls in case where the channel is from NLOS condition. The path loss for distance d between nodes calculates to [11]:

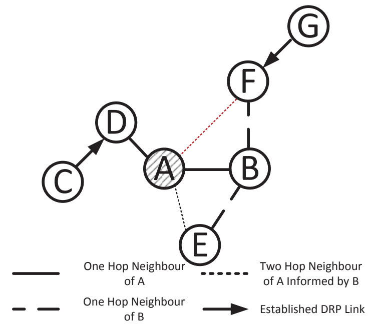


Fig. 3: Scenario with Exposed Nodes.

Algorithm 1 DRPNext

```
if tagged node is owner then
    for each foreign owner in BG do
        Check if foreign target is in BG too()
        if foreign target not in BG then
            if target != neighbor to foreign owner then
                consider foreign target as exposed
            end if
        end if
    end for
end if
if tagged node is target then
    for each foreign target in BG do
        Check if foreign target is neighbor to owner()
        if foreign target not neighbor to owner then
            if tagged node != neighbor to foreign owner then
                consider foreign target as exposed
                propose MAS in DRPavail as reusable
            end if
        end if
    end for
end if
```

$$L(d) = 20 \cdot log\left(\frac{4\pi}{c_0}\right) + 10 \cdot A \cdot log(d) + 10 \cdot B \cdot log(f) + C \quad (1)$$

where log-normal distributed shadowing loss C with zero mean and standard deviation σ is assumed, c_0 is the speed of light and f the radio frequency. The parameter values A, B and C are obtained from [12] and given in Table I. With $C \neq 0$ the beacon range r_{bg}, where nodes receive Beacons from other nodes in its BG, is not a fully closed region with constant radius, hence for analytical study, $L(d)$ is calculated from a Mean Path Loss UWB Channel Model (MPCM), where mean $\overline{L}(d)$ is:

$$\overline{L}(d) = P_{LOS}(d) \cdot L_{LOS}(d) + (1 - P_{LOS}(d)) \cdot L_{NLOS}(d) \quad (2)$$

Channel condition P_{LOS} and P_{NLOS} probabilities are shown in Fig. 4 and path losses $L_{LOS}(d)$ and $L_{NLOS}(d)$ are calculated from (1) assuming parameter values for MPCM given in Table I.

VI. Analytical Study

DRPNext recognizes exposed nodes and considers MASs reserved by exposed nodes for data frame transmission, thus lowers MAS reuse distance in network scenarios where the connectivity $c_f < 1$ and raises question for interference, which

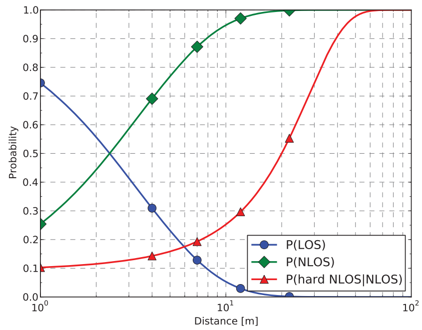


Fig. 4: NLOS and LOS Probabilities versus Distance.

TABLE I: Channel Model Parameter [12], [11]

UCM ($r_{bg} = 14\,\mathrm{m}$)	A	B	C
LOS	1.3	0.8	$\sigma = 2.6$
NLOS	2.3	0.8	$\sigma = 2.4$
Hard NLOS	4.1	0.8	$\sigma = 1.8$
MPCM ($r_{bg} = 16\,\mathrm{m}$)	A	B	C
LOS	1.3	0.8	0
NLOS	2.3	0.8	0

is addressed in this Section. Infinitesimal distance between the owner and the target of a DRP link is assumed. It increases the interference from neighboring nodes' data frame transmissions to maximum power, because the BGs of owner and target overlap completely, therefore limiting the area in which nodes respect MAS reservation to one single area with radius r_{bg}, the target's beacon range [13]. The connectivity of a network is:

$$c_f = \frac{\sum_{i=1}^{N} M_i}{N(N-1)} = \frac{\pi r_{bg}^2 \cdot \rho - 1}{\pi r_k^2 \cdot \rho - 1} \approx \frac{r_{bg}^2}{r_k^2} \tag{3}$$

where $N = \pi r_k^2 \cdot \rho - 1$ is the number of nodes in circular area with radius r_k, M_i the number of nodes in BG of Node i, ρ the node density and radius r_{bg} the beacon range. In Fig. 5 N nodes are randomly positioned with uniform distribution within a circular area with $r_k = n \cdot r_{bg}$ and $n = \{1, 2, \ldots\}$. Node A is positioned in the middle of the scenario. From Node A's point of view:

$$N_1 = (1 - c_f) \cdot N \tag{4}$$

N_1 nodes are not in its one hop BG neighborhood. From N_1, one or more nodes can interfere Node A's data frame transmission through a spatial reuse of the same MAS for DRP data frame transmission. If Node B interferes Node A, a second interferer Node C is outside Node A's BG and outside of the BG of Node B. The number of nodes neither in Node A's nor in Node B's BG is:

$$\begin{aligned}\widetilde{N_2} &= (1 - c_f)^2 \cdot N \\ N_2 &= \widetilde{N_2} + (N_1 - \widetilde{N_2}) c_f\end{aligned} \tag{5}$$

$\widetilde{N_2}$ is the number of nodes not within the BGs under the restriction, that both BGs do not overlap. Overlapping BGs

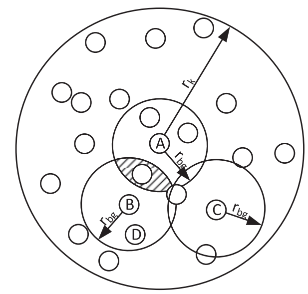


Fig. 5: Scenario with N Nodes randomly positioned in Area with Radius r_k.

lead to miscalculation because nodes in the intersection, the shaded area depicted in Fig. 5, are counted twice, which is corrected in N_2. This calculation can be iteratively continued:

$$\begin{aligned}\widetilde{N_3} &= (1 - c_f)^3 \cdot N \\ N_3 &= \widetilde{N_3} + (N_2 - \widetilde{N_3}) c_f + (N_1 - N_2) c_f^2\end{aligned} \tag{6}$$

and in general for $k \geq 3$:

$$N_k = N(1 - c_f)^{k+1} + N_{k-1} c_f + \sum_{i=1}^{k-2} (N_i - N_{i+1}) c_f^{k-i} \tag{7}$$

$I_{\mathrm{MAS}} = 256$ [6] is the number of MASs in the SF. A node, choosing randomly one MAS for DRP data frame transmission, excludes reserved MASs by nodes in its BG from DRP reservation, thus limits the available MASs for each node in the scenario to mean d_{MAS}:

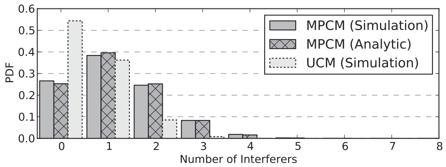
$$\begin{aligned}d_{MAS} &= \frac{1}{N_{BG}} \sum_{i=0}^{N_{BG}-1} I_{\mathrm{MAS}} - i \\ N_{BG} &= c_f \cdot N\end{aligned} \tag{8}$$

where N_{BG} is the number of nodes in BG. Concerning Node A in Fig. 5, the probability that exactly $k = \{0, 1, 2, \ldots\}$ nodes choose the same MASs for DRP data frame transmission and interferes with Node A's DRP data frame transmission follows:

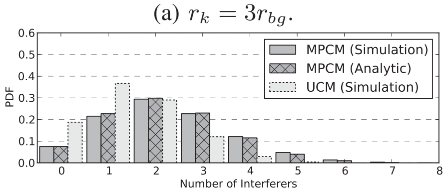
$$\begin{aligned}p_k &= \binom{N_k}{k} \left(\frac{1}{d_{MAS}}\right)^k \left(1 - \frac{1}{d_{MAS}}\right)^{N_{k+1}} \quad k \geq 1 \\ p_0 &= 1 - \sum_{k=1}^{\infty} p_k\end{aligned} \tag{9}$$

If $k = 1$: Node B is a node from $N_k = N_1$ nodes not in BG of Node A, choosing with probability $\frac{1}{d_{MAS}}$ Node A's MAS for DRP data frame transmission. The remaining number of nodes able to choose the same MAS is $N_{k+1} = N_2$. For other nodes in Node B's BG, Node D in Fig. 5, the probability to choose subsequently the same MAS is 0, because they defer from trying to reserve the respective MAS.

Monte Carlo Experiment: Results obtained from (4) to (9) are compared to results from a Monte Carlo experiment, stated in Algorithm (2), assumes node density $\rho = 0.05\,{}^{1}/_{\mathrm{m}^2}$ and



(a) $r_k = 3r_{bg}$.



(b) $r_k = 4r_{bg}$.

Fig. 6: PDF showing Number of Interferer for UCM and MPCM.

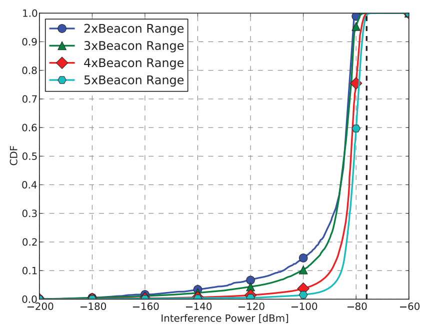


Fig. 7: CDF Interference Power at Position of Node A considering UCM.

uses parameter values given in Table I. A BG comprises for UCM 30 and for MPCM 40 nodes, leading to 35 % and 46 % BG utilization [6]. The Monte Carlo experiment comprises 20 scenario instances, each represented by random node positions, derived from different seeds. For every scenario instance, the order in which nodes choose MAS randomly is changed by 2000 trials. Fig. 6 shows the Probability Density Functions (PDFs) for number of interfering nodes. For $r_k = 3r_{bg}$, depicted in Fig. 6(a), the probability that one node interfere with Node A's DRP data frame transmission is $p_1 = 0.39$, whereas $p_2 \approx 0.24$, in scenarios where MPCM is assumed. The probabilities p_k for scenarios where UCM is used differ from MPCM, noticeable for $p_0 = 0.55$. Fig. 6(b) shows results for $r_k = 4r_{bg}$, where $p_1 = 0.37$ for UCM and $p_1 \approx 0.23$ for MPCM. In scenarios where the beacon range spans a fully closed region, that is for MPCM, the results from Monte Carlo experiments confirm results obtained analytically from (9). Results for UCM show p_k with $k \geq 2$ to be lower than results obtained from scenarios, where MPCM is assumed. Moreover, Fig. 7 shows the Cumulative Distribution Function (CDF) of the interference power I on Node A's position, assuming UCM for varying r_k. It is obvious from the results, that the interference power can be approximated by the step function with $I_{max} \approx -76\,\mathrm{dBm}$, if r_k is sufficiently large.

Algorithm 2 Monte Carlo Experiment

```
for all seeds do
    SetOfNodes = locate nodes to scenario()
    set NodeA to (0,0)
    for all trials do
        while nodes left in SetOfNodes do
            choose from SetOfNodes node i randomly
            I_MAS,i = 256 - MASs marked reserved in BG for node i
            reserve one MAS from I_MAS,i
        end while
        for nodes in scenario do
            count nodes choosing NodeA MAS
        end for
    end for
end for
calculate PDF for p_k with k = {0, 1, ...}
```

VII. Evaluation

This Section evaluates ECMA-368 system performance in home environment scenarios, where nodes gain channel access from DRPNext and standard DRP. Results on system capacity are obtained from an extension to the WiMedia MAC Simulator (WiMeMAC) [14], the ECMA-368 module of the open Wireless Network Simulator (openWNS) [15]. The studied scenario assumes parameter values given in Table II and considers UCM with parameters from Table I. The number of nodes within the network is increased from 20 to 50 pairs, where a node pair consists of a reservation owner and reservation target, performing data frame transmission from owner to target. Fig. 8 shows system throughput in saturation, that is the maximum offered traffic that can be carried by each node in the scenario, while increasing number of nodes. For standard DRP, throughput decreases from $205\,\mathrm{Mb/s}$ to $170\,\mathrm{Mb/s}$, whilst for DRPNext system throughput remains constant $250\,\mathrm{Mb/s}$ for 20 to 40 node pairs and decreases to $235\,\mathrm{Mb/s}$ for 50 node pairs. The probability of exposed nodes increases with number of nodes in the scenario, thus DRPNext enables a system capacity gain of about $30\,\%$ for increasing number of nodes. Overhead from management data transmission is caused to the network from Beacon transmission, which limits time duration remaining for user data frame transmission in the SF. Hence system capacity decreases with increasing number of nodes. Comparing the results for 40 and 50 node pairs show, that the difference in terms of system throughput remains constant $\approx 65\,\mathrm{Mb/s}$, which indicates equal overhead from Beacon transmission, regardless of the MAC protocol in use. Fig. 9 shows the CDF of the reuse distance, where the distance for less than $80\,\%$ of nodes performing DRP and DRPNext

TABLE II: Simulation Parameter.

Parameter	Values
Scenario Size	$20\,\mathrm{m} \cdot 20\,\mathrm{m}$
Number of Nodes	40, 60, 80, 100
Distance between owner and target	$2\,\mathrm{m}$ [16]
Number of Seeds	80
MCS	$53\,\mathrm{Mb/s} - 480\,\mathrm{Mb/s}$ [17]
Frame Size	1500 B
Frequency	3.96 GHz
Positioning of Nodes	Uniformly Distributed
Channel Model	UCM

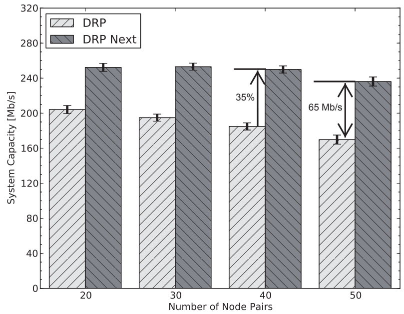


Fig. 8: Maximum System Throughput in Saturation, given 95% Confidence Interval.

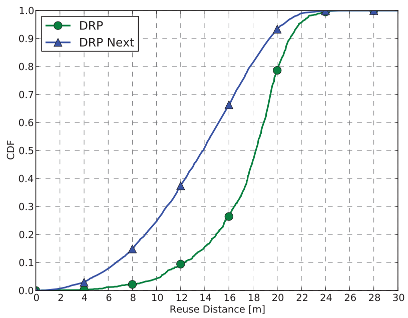


Fig. 9: CDF of Reuse Distance.

channel access in the scenario is $17.5\,\mathrm{m}$ for DRPNext and $20\,\mathrm{m}$ for standard DRP . The mean value decreases from $17.4\,\mathrm{m}$ to $13.4\,\mathrm{m}$, if channel access is gained from DRPNext. The PDF of the MCS in use is depicted in Fig. 10 for 50 node pairs in the scenario. It shows only a minor impact of interference to the MCS distribution in home environment scenarios, where DRPNext is used. Even in case where I_{max} shown in Fig. 7 is assumed, a significant number of nodes is not forced to use MCSs offering less data rates. The MCS distribution which assumes I_{max} is calculated regarding path loss distribution obtained from (1) for UCM.

VIII. Conclusion

This paper contributes an improvement to the DRP to mitigate exposed nodes impact on system capacity in ECMA-368 UWB WPAN scenarios. The system capacity is increased by more than $30\,\%$, shown in Fig. 8, in home environment scenarios where nodes gain channel access from DRPNext. Furthermore, an analytical study is given, to calculate the number of interfereing nodes, which motivates the next step to enable nodes to decline MASs reuse, if the SINR at the reservation target is below a predetermined threshold.

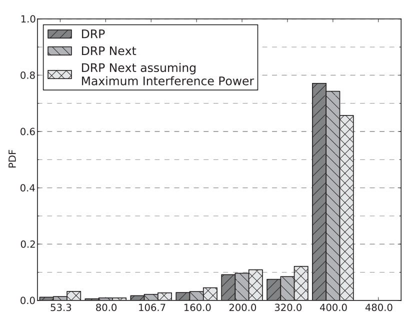


Fig. 10: PDF of MCS used by Nodes in the Scenario.

References

[1] L. B. Jiang and S.-C. Liew, "Improving Throughput and Fairness by Reducing Exposed and Hidden Nodes in 802.11 Networks," *Mobile Computing, IEEE Transactions on*, vol. 7, no. 1, pp. 34–49, 2008.

[2] Z. Kewang, Z. Deyun, and J. Weihua, "Mitigation of Exposed Terminal Problem Using Packet Sensing," in *Communication Networks and Services Research Conference*, 2008, pp. 263–269.

[3] D. Shukla, L. Chandran-Wadia, and S. Iyer, "Mitigating the Exposed Node Problem in IEEE 802.11 Ad Hoc Networks," in *Computer Communications and Networks. Proceedings. The 12th International Conference on*, 2003, pp. 157–162.

[4] Y. Zhou and S. Nettles, "Balancing the Hidden and Exposed Node Problems with Power Control in CSMA/CA-based Wireless Networks," in *Wireless Communications and Networking Conference*, vol. 2, 2005, pp. 683–688 Vol. 2.

[5] K. Mittal and E. Belding, "RTSS/CTSS: Mitigation of Exposed Terminals in static 802.11-based Mesh Networks," in *Wireless Mesh Networks. 2nd IEEE Workshop on*, 2006, pp. 3–12.

[6] *Standard ECMA-368: High Rate Ultra Wideband PHY and MAC Standard*, 3rd ed., ECMA International, December 2008.

[7] *IEEE 802.11-2007: IEEE Standard for Information technology - Telecommunications and information exchange between systems - Local and metropolitan area networks - Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Laye (PHY) Specification*, IEEE, 2007.

[8] G.R. Hiertz, J. Habetha, P. May, E. Weiss, R. Bagul, S. Mangold, "A Decentralized Reservation Scheme for IEEE 802.11 Ad Hoc Networks," in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Beijing, China, September 2003.

[9] J. Ahmadi-Shokouh and R. C. Qiu, "Ultra-Wideband (UWB) Communications Channel Measurements — A Tutorial Review," *Int. J. Ultra Wideband Communications and Systems*, vol. 1, pp. 11–31, 2009.

[10] B. Gaffney, "Combined LOS and NLOS UWB Channel Model," http://www.decawave.com/assets/files/products/D0712003WP1-Combined-LOS-NLOS-UWB-Channel-Model.pdf, Januar 2008.

[11] J. Reed, *Introduction to Ultra Wideband Communication Systems*. Prentice Hall Press Upper Saddle River, NJ, USA, 2005, pp. 73–93.

[12] T. Zwick, C. Fischer, and W. Wiesbeck, "A Stochastic Multipath Channel Model Including Path Directions for Indoor Environments," *Selected Areas in Communications, IEEE Journal on*, vol. 20, no. 6, pp. 1178 – 1192, August 2002.

[13] H. Rosier and K. Sambale, "Performance Evaluation of Channel Access Protocols in Overlapping ECMA-368 Wireless Personal Area Networks," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2012 IEEE 23rd International Symposium on*, 2012, pp. 362–368.

[14] H. Rosier, "ECMA-368 (WiMedia) System Level Simulation Module," https://launchpad.net/openwns-wimemac/, 2010, [Online; accessed 19-April-2013].

[15] D. Bueltmann, M. Muehleisen, K. Klagges, M. Schinnenburg, "openWNS - open Wireless Network Simulator," in *15th European Wireless Conference, Electronic Proceedings*, Aalborg, Denmark, May 2009, pp. 205–210. [Online]. Available: http://www.comnets.rwth-aachen.de

[16] R. Kraemer and M. D. Katz, Eds., *Short-Range Wireless Communications*. John Wiley & Sons, Southern Gate, Chichester, West Sussex, 2009.

[17] S. Max and Y. Zang, "OFDM-UWB Physical Layer Emulation for Event-based MAC Simulation," in *Proceedings of the 17th Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Helsinki, Finnland, September 2006, p. 5. [Online]. Available: http://www.comnets.rwth-aachen.de