Performance Analysis of Synchronization Frame Based Interference Mitigation in 60 GHz WPANs

Xueli An, Chin-Sean Sum, R. Venkatesha Prasad, Hiroshi Harada, and Ignas Niemegeers

***Abstract*—60 GHz radio is a promising technology since it can offer multi-Gbps data rate. However, 60 GHz radio based transmission is easily disturbed by co-channel interference (CCI). In this letter, a novel analytical model is provided to investigate the performance of using synchronization (sync) frames to mitigate CCI. The performance improvement while using sync frames is demonstrated in terms of throughput and the guaranteed transmission distance.**

***Index Terms*—WPAN, piconet coexistence, 60 GHz radio, synchronization frame, co-channel interference.**

I. INTRODUCTION

SIXTY GHz radio is a promising technology due to its potential to provide multi-Gbps based data rate. It is capable to support emerging wireless multimedia applications like uncompressed high definition video streaming. However, due to the stringent link budget, 60 GHz communication is very fragile to the co-channel interference (CCI). An undesired CCI may easily compromise the quality of the 60 GHz system [1]. For this reason, an interference mitigation mechanism has to be delicately designed to ensure reliable communications in 60 GHz systems. Interference issues, especially for wireless personal area networks (WPANs), have been investigated in many earlier works [2]−[4]. However, to the best of our knowledge, none of them have provided special treatment for mitigating interference in 60 GHz WPANs. IEEE 802.15.3 [5] defines a well-accepted MAC layer protocol for WPANs. The network topology of IEEE 802.15.3 featured WPANs is based on piconet formation, which consists of a piconet coordinator (PNC) and several slave devices within the transmission range of the PNC. The PNC allocates the channel access time for the slave devices within its domain in a TDMA fashion. It manages its piconet by periodically broadcasting beacons, which contain the timing and management information of the piconet. Devices within a piconet communicate with each other through direct links in the time slots allocated to them. Two independent piconets are autonomously managed by their respective PNCs. IEEE 802.15.3c [6] was formed to standardize 60 GHz featured WPANs. Based on the IEEE 802.15.3 MAC, the IEEE 802.15.3c standard defined a new frame format called as synchronization frames (sync frames) to mitigate CCI. Sync frames can be considered as the copies of beacons, which contain the timing information of a piconet. The coverage range of a piconet can be extended by broadcasting the sync frames through the slave devices. For a device, it cannot become a PNC if it receives any beacons or sync frames from the other piconets. However, the performance modeling and evaluation of this solution has not been done in the IEEE 802.15.3c activities.

In this letter, a novel theoretical work is proposed to model CCI and its influence on the system capacity using the bit error rate (BER) derived from a 60 GHz featured physical layer and channel model. Our work is the first attempt to quantify the performance of using sync frames to support coexisting 60 GHz WPANs. Usually due to the complexity in analysis, the conventional methods to model the interference for coexisting systems do not consider the shadowing effect in radio propagation model, e.g. [2], [4]. This gap is closed in our analytical model wherein the log-normal shadowing radio propagation model is used.

II. ANALYTICAL MODEL

A. Interference Indication Function Derivation

When a device is powered on, first it scans the possible channels to detect if there are any surrounding piconets. If the device receives a beacon within a certain scanning time T_{scan}, it associates with the detected PNC to join in its piconet, where T_{scan} is the time duration to transmit n_b beacons. Otherwise, it assumes that the channel is free, and it can become a PNC by broadcasting its own beacons. To study the interference situation with the existence of a single interfering source, PNC v is assumed to be the primary PNC and it is located at the center of an area with radius R. Its beacon range is denoted as r_{th}, and we have $r_{th} < R$.

$\mathbb{P}_r(d)$ denotes the received signal strength (in dB) at the receiver which is d meters away from the transmitter, $\mathbb{P}_r(d) = \mathbb{P}_t + G - PL_0 - 10n\log_{10}(d) + X_\sigma$, where $\mathbb{P}_t$ is the transmission power, G is antenna gain, PL_0 is the reference path loss at 1 m, and n is the path loss exponent. X_σ is a zero mean Gaussian distributed random variable with standard deviation σ [8]. Hence, we denote $\mathbb{P}(d) \backsim \mathcal{N}(\mu(d), \sigma)$ with mean $\mu(d) = \mathbb{P}_t + G - PL_0 + 10\log_{10}(d^{-n})$. To correctly receive a signal from the transmitter, $\mathbb{P}_r(d)$ should be higher than the receiving threshold γ_{th}. Hence, the probability that a link exists between the transmitter and receiver is given by [7],

$$\begin{aligned} q_l(d,n) &= \frac{1}{\sigma\sqrt{2\pi}} \int_0^\infty \exp\left[-\frac{(t - 10\log_{10}(\hat{d}^{-n}))^2}{2\sigma^2}\right] dt \\ &= \frac{1}{2}\left(1 - \operatorname{erf}\left(\frac{10n\log_{10}(\hat{d})}{\sqrt{2}\sigma}\right)\right), \end{aligned} \tag{1}$$

where we define $\hat{d} = d/r_{th}$ and $r_{th} = 10^{\frac{\varpi}{10n}}$, in which $\varpi = \mathbb{P}_t + G - PL_0 - \gamma_{th}$, r_{th} is the beacon range without considering the log-normal shadowing effect.

Let device m be the slave device of PNC v and it is located at a radius r_m from v. The link between v and m is considered as the target link with m as the transmitter and v as the

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Manuscript received January 4, 2010. The associate editor coordinating the review of this letter and approving it for publication was Y.-C. Wu.

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Digital Object Identifier 10.1109/LCOMM.2010.05.100012

receiver. Other than this target link, there is another device (here i), which is randomly placed and is uniformly distributed within the circular area with radius R. The probability for device i to become an interfering PNC is,

$$p_c = \left[\prod_{k=0}^{m_s} (1 - q_l(r_{i,k}, n_{i,k})) \right]^{n_b}, \tag{2}$$

where, m_s is the number of slave devices relaying sync frames within the primary piconet, for the scheme without using sync frames, $m_s = 0$. $r_{i,0}$ denotes the distance from device i to PNC v and $r_{i,k}$ is the distance from device i to the other relaying devices, where $k \in [1, m_s]$. Because the channel quality between device i and the PNC or relaying devices might be different, $n_{i,k}$ is used to specify the path loss exponent for each link. The CCI is quantified as the ratio of the undesired signal power and the desired signal power. On the condition that device i is an interfering device, and the distance between device i and PNC v is r_i, where r_i is short for $r_{i,0}$, the CCI (in dB) is represented as $\zeta(r_i, r_m) = \mathbb{P}_r(r_i) - \mathbb{P}_r(r_m)$, where $\mathbb{P}_r(r_m)$ is the received power (in dB) from the target transmitter and $\mathbb{P}_r(r_m) \backsim \mathcal{N}(\mu(r_m), \sigma_t)$, $\mathbb{P}_r(r_i)$ is the received power (in dB) from the interfering source and $\mathbb{P}_r(r_i) \backsim \mathcal{N}(\mu(r_i), \sigma_i)$. To achieve a certain level of BER, ζ should be smaller than a required threshold ζ_{th} [1]. Therefore, device i has a probability ξ_c to disturb the receiver at PNC v, which is given by,

$$\begin{aligned} \xi_c(r_i, r_m) &= \Pr\left[\zeta(r_i, r_m) > \zeta_{th}\right] \\ &= \frac{1}{2}\left(1 + \mathrm{erf}\left(\frac{10\log_{10}(\hat{r_i}) - \zeta_{th}}{\sqrt{2(\sigma_t^2 + \sigma_i^2)}}\right)\right), \end{aligned} \tag{3}$$

where $\hat{r_i} = r_m^{n_t}/r_i^{n_i}$, factor n_t is the path loss exponent for target link between m and v, and n_i is the path loss exponent for the interfering link between n and v. Here, we define an interference indication function $\mathbb{F}(.)$ to express the possible interference caused within the network as,

$$\mathbb{F}(r_m) = \int_0^{2\pi} \int_0^R p_c(x)\xi_c(x, r_m) f(x) f(\alpha) dx d\alpha, \tag{4}$$

where $f(x) = 2x/R^2$ and $f(\alpha) = 1/2\pi$. To demonstrate the performance of $\mathbb{F}(r_m)$ by using sync frames, we considered three slave devices of PNC v to relay sync frames, and they were placed at equal distances from each other on the circumference of the circle of 8 m from v. We compared $\mathbb{F}(r_m)$ with and without using sync frames while varying path loss exponent for the interfering link, and the results are shown in Fig. 1. It is observed that, sync frames can effectively reduce the interference level. The beacon range influence is depicted in Fig. 2 when the transmission distance of the target link r_m is fixed at 5 m. What needs to be noticed here is that we denote the sync frame range to be same as beacon range. Obviously, the bigger the beacon range, the lower is the interference level.

B. Relationship between CCI and Throughput

In a co-operating system, the CCI for a system with multiple interfering sources can be represented as,

$$\zeta(r_m) = 10\log_{10} \frac{\sum_{i=1}^N \mathrm{P}_r(r_i)}{\mathrm{P}_r(r_m)}, \tag{5}$$

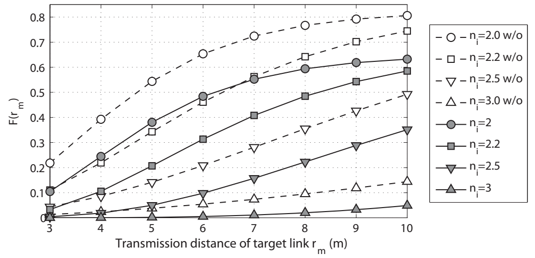

Fig. 1. $\mathbb{F}(r_m)$ comparison between using sync frame and without using sync frame, 3 relaying devices, $\gamma_{th} = -70$ dBm, $\zeta_{th} = -15$ dB, $\sigma_t = 1.3$, $\sigma_i = 2.7$, $n_t = 2$, $r_{th} = 10$ m, $R = 30$ m, $n_b = 3$.

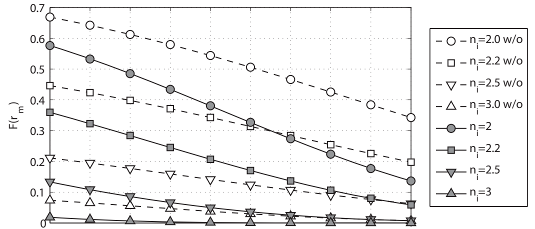

Fig. 2. Beacon range influence on $\mathbb{F}(r_m)$, the same parameter specification as the previous figure, $r_m = 5$ m.

where $\mathrm{P}_r(r_m)$ is the desired signal strength (in watt) and $\mathrm{P}_r(r_i)$ is the received signal strength (in watt) from the i^{th} interfering source. The distance between the interfering device and the target receiver is r_i. For an individual interfering source i, $\mathrm{P}_r(r_i)$ could be represented as a log-normal variable with mean ω_i and standard deviation ν_i, where $\omega_i = \exp(\mu_i + \sigma_i^2/2)$ and $\nu_i = (\exp(\sigma_i^2) - 1)\exp(2\mu_i + \sigma_i^2)$. The summation of the log-normally distributed interfering power can be assumed as a log-normally distributed variable $\mathbb{L} \backsim \text{Log-}\mathcal{N}(\mu_l, \sigma_l)$ [9]. By using Fenton-Wilkinson (FW) approximation model [10], we can have $\mu_l = 2\ln u_1 - \frac{1}{2}\ln u_2$ and $\sigma_l = (\ln u2 - 2\ln u1)^{\frac{1}{2}}$, where $u_1 = \sum_{i=1}^N \exp(\omega_i + \nu_i^2/2)$ and $u_2 = \sum_{i=1}^N \exp(2\omega_i + 2\nu_i^2) + 2\sum_{i=1}^{N-1}\sum_{j=i-1}^{N} \exp(\omega_i + \omega_j)\exp(\frac{1}{2}(\nu_i^2 + \nu_j^2))$. FW model has a good accuracy when the standard deviation of log-normal components are less than 4 dB [7].

The current CCI level ζ and the selected modulation and coding (MCS) scheme κ_i determine the achievable BER e_{κ_i} at the target link, which is denoted as $e_{\kappa_i} = f_{\kappa_i}(\zeta)$. The mapping function $f_{\kappa_i}(.)$ is determined by the physical layer. We use the physical layer model specified by [1]. The modulation schemes employed are BPSK, QPSK, 8PSK and 16QAM, and their corresponding modulation level L_m is 1,2,3 and 4. The code rate is 0.937. The pulse filtering strategy is root-raised cosine in both the transmitter and receiver with roll-off factor of 0.25. The 60 GHz power amplifier at the front end of the transmitter has a power output backoff of 3 dB for LOS environment and 5 dB for NLOS environment. Particularly in NLOS environment, the receiver employs frequency domain equalization (FDE) to mitigate multipath fading by using guard interval of 128 chips prepended to the data. The FFT block for the FDE is 512. The propagation environment is residential environment for both AWGN/LOS and NLOS (*i.e.* CM2.3 [6]). The resultant BER and CCI performance is shown in Fig. 3, in which it indicates that to achieve the target

BER of 10^{-4}, the CCI should be lower than -15.5 dB in LOS environment and lower than -14.6 dB in NLOS environment. For a memoryless channel, we can assume that the bit errors are not correlated and they are uniformly distributed within a packet. Under this assumption, the resultant packet error rate is given by $P_e^{\kappa_i}(l) = 1-(1-e_{\kappa_i})^l$, where l is the frame length (in bits). Therefore, the system throughput without considering any automatic repeat request technique can be approximated as $C = (1-\eta)R_{\kappa_i}(1-P_e^{\kappa_i}(l))$, where R_{κ_i} is the data rate by using MCS κ_i, and η is the proportion of overhead, $\eta = \frac{t_o}{l/R_{\kappa_i}+t_o}$, where t_o is the sum of the duration of the packet preamble, header, and minimum inter-frame spacing length. R_{κ_i} is given by $R_{\kappa_i} = S_{BW} L_m r_c \frac{L_{sub}-L_{gi}}{L_{sub}}$, where S_{BW} is the symbol bandwidth, L_m is the modulation level, r_c is the code rate. L_{gi} and L_{sub} are the length of guard interval and FDE sub-block.

A set of simulations are carried out in MATLAB. A circular network with N devices is generated, where $N > 2$. The position of the target transmission pair is fixed, in which, PNC v is located at the center of the network and its target transmitter is located at radius r_m. The position of the other $N-2$ devices are sequentially generated, and they are uniformly distributed within the circular network. Two network topology formation mechanisms are considered in the simulations i.e., with or without sync frames. For the scenario without using sync frames, after a device is generated, it associates with the closest PNC it can reach and becomes a slave device of that PNC. If there is no surrounding PNC, it becomes a PNC. For the scenario with using sync frames, after a device is generated, it associates with the closest PNC. If this device is not within the beacon range of any piconets and it receives sync frames from relaying devices, it associates with the closest relaying device. If this device is not within the coverage range of any beacon or sync frames, it becomes a PNC.

After formatting the network topology, each PNC outside the primary piconet is assumed as the transmitter in its piconet, and it selects its closest slave device as the receiver. The FW model is used to approximate the interference power. Assume that all the transmission pairs communicate simultaneously to create the worst interference situation for the target link in the center. Therefore, the capacity of the target link could be considered as a lower bound for the link capacity with transmission distance r_m. It is assumed that, all the transmission pairs can select the MCS that provides the highest data rate according to their current CCI level.

The cumulative distribution function (cdf) of the CCI at PNC v is shown in Fig. 4 (a) when the transmission distance of the target link r_m is fixed at 0.8 m. It is observed that, the CCI performance is dramatically improved using sync frames in both LOS and NLOS channel model. Figure 4 (b) illustrates the influence of the CCI on the guaranteed transmission distance of the target link, in which, the achievable throughput is plotted in the case that r_m is varied from 0.05 m to 6 m. In each run of simulation, throughput is calculated based on the mean CCI and the MCS that provides the highest throughput. The guaranteed maximum transmission distance of the target link is denoted as r_{max}, which is obtained with the targeted BER as 10^{-4}. The factor r_{max} is the transmission distance threshold. If $r_m > r_{max}$, the link is disconnected. Without using sync frames, r_{max} is 1 m for LOS channel, and 3.05 m for NLOS channel. Using sync frames, r_{max} is 1.85 m for LOS and 6 m for NLOS. This shows that r_{max} significantly increases when sync frames are used. Due to the fact that PNC v is expected to experience the highest amount of interference, r_{max} can be viewed as the lower bound of the guaranteed transmission distance within a piconet.

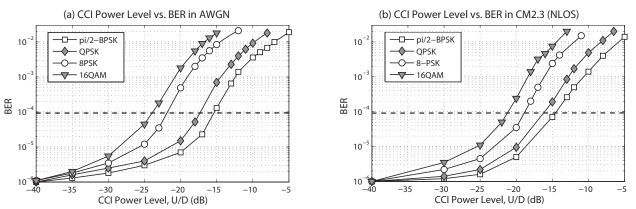

Fig. 3. CCI power level in AWGN and residential NLOS channel.

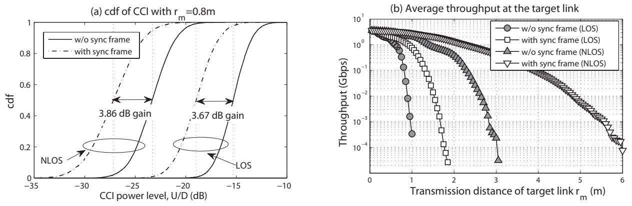

Fig. 4. Interference level and achievable throughput, the same parameter specification as Fig. 1, moreover, $N = 100$, $n_i = 2.7$, $t_o = 2\,\mu$s, $l = 2048$ bytes, $S_{BW} = 1728$ MHz, 10000 simulation iterations.

III. CONCLUSION

Synchronization (sync) frames are devised to mitigate co-channel interference (CCI) in 60 GHz WPANs. In this letter, a theoretical model is provided to analyze the influence of CCI with and without sync frames. For a certain size of network, a lower bound on the guaranteed transmission distance is derived.

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