Characterization of Multi-Channel Interference

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***Abstract*— Multi-channel communication protocols in wireless networks usually assume perfect orthogonality between wireless channels or consider only the use of interference-free channels. The first approach may overestimate the performance whereas the second approach may fail to utilize the spectrum efficiently. Therefore, a more realistic approach would be the careful use of interfering channels by controlling the interference at an acceptable level. We present a methodology to estimate the packet error rate (PER) due to inter-channel interference in a wireless network. The methodology experimentally characterizes the multi-channel interference and analytically estimates it based on the observations from the experiments. Furthermore, the analytical estimation is used in simulations to derive estimates of the capacity in larger networks. Simulation results show that the achievable network capacity, which is defined as the number of simultaneous transmissions, significantly increases with realistic interfering channels compared with the use of only orthogonal channels. When we consider the same number of channels, the achievable capacity with realistic interfering channels can be close to the capacity of idealistic orthogonal channels. This shows that overlapping channels which constitute a much smaller band, provides more efficient use of the spectrum. Finally, we explore the correctness of channel orthogonality and show why this assumption may fail in a practical setting.**

I. Introduction

The use of multiple frequency channels is an efficient way to improve the capacity of wireless networks by supporting simultaneous transmissions on different channels. The network throughput can significantly be improved by enhancing the utilization of the bandwidth which is a scarce resource in wireless communication [1]. There exists a significant number of multi-channel MAC and routing protocols for wireless networks [2]–[7] in the literature.

The research community working on multi-channel protocols either assume that channels are perfectly orthogonal (interference-free) or consider the use of only orthogonal channels. Assumption of perfect orthogonal channels fails in practice since radio signals are not bound to a single point in the spectrum but are distributed around a mid frequency so that channel overlap/interference is examined between adjacent bands. On the other hand, the use of only orthogonal channels cannot utilize the spectrum efficiently. For instance, the 802.11b standards define 11 channels of which only 3 are orthogonal. Most users configure their wireless interfaces to use one of these 3 channels. However, careful use of not only 3 channels but all 11 channels with a tolerable level of interference can significantly improve the system performance [8].

In this paper, we explore how we can achieve efficient use of the wireless spectrum and investigate what we can gain by the careful use of overlapping channels compared with the use of only interference-free channels. We first introduce a methodology to estimate the inter channel interference that occurs with the simultaneous transmissions on different channels. The methodology experimentally characterizes the multi-channel interference and analytically estimates it based on the observations from the experiments. Analytical model is then used in simulations to investigate the impact of channel orthogonality on the network capacity and to show the improvements on the network performance.

In general, interference between overlapping channels is influenced by the transmission power, distance between transmitters, channel spacing and transceiver characteristics. One approach to evaluate the inter-channel interference is experimentation. We have investigated the data link interference behavior of a multi-channel system with an example radio platform [9]. We define the interference level as the packet error rate (PER) at the receivers. We have shown that there is a high correlation between channel distance and spatial distance according to the level of interference among simultaneous transmissions. Hence, channel spacing can be adjusted according to the spatial distances so that multiple concurrent transmissions can be performed with a tolerable level interference.

Experimentation of wireless networks is a valuable approach since it overcomes the assumption of unrealistic/idealistic RF models [10]. However, experimentation usually takes long and it is difficult to generalize/reproduce the results due to the large variety of settings. Therefore, it is difficult to compare the results which would be easy with an analysis or simulation. The question that we try to answer is: "Can we analytically estimate the interference such that the estimations comply with the results of the experiments?".

We explore a methodology to analytically estimate the multi-channel interference. The method calculates Signal-to-Interference Ratio (SIR) according to the spatial distances between the nodes. Based on the SIR values, bit error rate (BER) is calculated as a function of the channel distances between the nodes and the transceiver characteristics. Finally, PER is calculated in terms of BER.

As mentioned, the analytical method should be simple but also should comply with the experimental observations. We verify the estimation by comparing the analytical results with the experimental results: On the average 90% of the results are

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found to be similar. We explain the comparisons in Section IV.

Furthermore, the analytical estimation is used in simulations to derive the performance in larger networks. First, we investigate the performance gains with the usage of overlapping channels over using only the orthogonal channels. In this case the network can make use of more channels and the capacity increase is inevitable [11]. Then, we investigate the relationship between channel orthogonality and the network capacity. In particular, we compare the achievable capacity with the same number of interference-free (orthogonal) channels and interfering (overlapping) channels. Simulation results show that given the same number of channels, the achievable network capacity with realistic interfering channels can be close to the capacity of idealistic orthogonal channels depending how much the receiver is prone to the interference or in other words how much channel overlap can be tolerated by the receiver. This shows that, if the transceiver is designed firm enough against the adjacent channel interference, channel orthogonality does not have a major impact on the achievable capacity. Overlapping channels which constitute a much smaller band, provides more efficient use of the spectrum. Finally, we investigate the correctness of schedules generated with the orthogonal frequencies assumption.

The rest of the paper is organized as follows: Section II presents the experimental results on the interference behavior between overlapping channels. Section III introduces the analytical estimation of packet error rate caused by inter-channel interference. Section IV includes the comparisons between the analytical estimation and the mentioned experiments to verify the estimation. Section V presents the simulation results on the capacity of overlapping channels. Section VI presents our conclusions.

II. Experiments

We have experimented the multi-channel interference behavior with an example radio platform [9], [12]. The primary objective of the experiments is to observe the level and the effect of adjacent spectrum interference.

We have used a typical radio platform [13] for wireless sensor networks which can adjust its operating frequency on different channels. The transceiver can operate on the 868/915 MHz ISM band with a 50kbps data rate. The modulation of the transceiver is Gaussian Frequency Shift Keying (GFSK). The transceiver automatically generates a preamble and CRC. An on-board dipole antenna is integrated. The radio frequency of the platform is adjustable. It provides 512 channels with 200kHz channel width.

In the experiments, there are three different roles of the nodes: transmitter, receiver, and jammer. The transmitter sends out packets with sequence numbers and the receiver operates

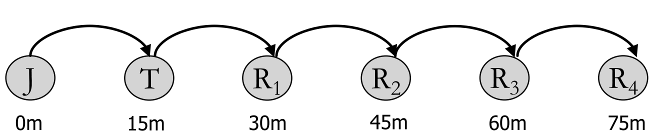

Fig. 1: Positions during the Experiments

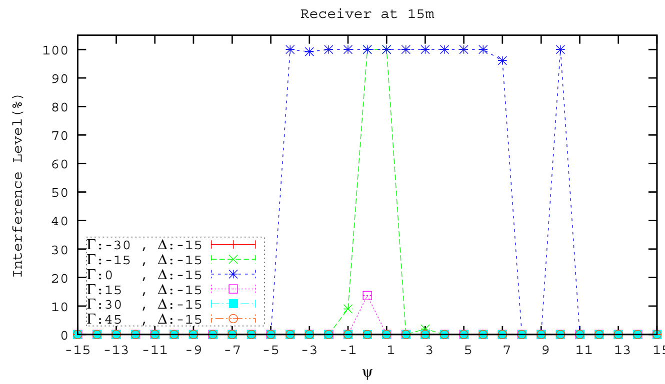

Fig. 2: Experimented PER versus channel spacing

on the same frequency as the transmitter and maintains a log of the received packets in its EEPROM. At the end of the tests, the data from the logger of a receiver is downloaded to be further analyzed. The jammer is also a transmitter whose operating frequency is adjusted to a different channel during the experiments. The jammer sends packets simultaneously with the transmitter, which allows us to observe the packet loss due to the interference between parallel transmissions on different channels. The position of the jammer is changed to observe the relationship between distance and channel spacing. Figure 1 shows how the nodes are located during the experiments (J:Jammer, T:Transmitter, R:Receiver). We have also varied the number of jammers in the experiments.

Figure 2 demonstrates an example set of PER results with a single jammer. The receiver is positioned 15 meters away from the transmitter (R1 on Figure 1). The x-axis (Ψ) shows the channel spacing between the transmitter and the jammer. Different lines represent different values of Γ, which is the physical distance between the jammer and the receiver. Δ represents the distance between the transmitter and the receiver in meters and is constant during this experiment. Note that these parameters can take negative values. For instance, when the jammer is positioned to the left of a receiver, Γ is negative and when the jammer is to the right of a receiver it has a positive value. The y-axis shows the interference (packet loss) at the receiver.

Different levels of interference are observed according to different values of channel spacing and physical distances. In the worst case, when the jammer is located next to the receiver ($\Gamma = 0$), there is interference if $-5 \leq \Psi \leq 8$. However, when the jammer is positioned further away (45m, $\Gamma = 45, \Delta = -15$), there is no interference even on the same channel. Note that, the interference level is asymmetric with respect to the operating frequency, such that different levels of interference occur between $-n \leq \Psi \leq n$, due to the asymmetric interference tolerance values of the transceiver.

As a result of the experiments we show that there is a high correlation between channel spacing and spatial distance. Hence, channel spacing can be adjusted according to the spatial distances so that multiple concurrent transmissions can be performed with minimum interference.

III. Analytical Estimation

Experimentation is a valuable approach to test the performance of wireless networks since it prevents the assumption of unrealistic/idealistic RF models [10]. On the other hand, due to the large variety of settings it is usually difficult to generalize/reproduce the results which would be easy with an analysis or simulation. Simulations have the advantage of evaluating the scalability of the new solutions. Considering the advantages/disadvantages of the different methods, we describe an analytical model which is verified by experimentation and tested with simulations in larger networks.

In this section, we explain the analytical method to estimate the packet error rate caused by interference due to (a) jammer(s) that simultaneously operates on a different channel in the same spatial domain. The method incorporates the parameters that impact the inter-channel interference: distances between transmitter(s), jammer(s) and receiver(s), channel distance between the transmitter(s) and the jammer(s), transmission power and the transceiver characteristics.

The method is briefly composed of the following steps:

- Given the values of transmission power and the distance between the nodes, we calculate the signal to interference ratio (SIR) at the receiver using a path loss model.
- We calculate the bit error rate (BER) as a function of the SIR according to the blocking values (a measure of how much interference can be tolerated due to the parallel transmissions on different channels) of the transceiver with the given channel distance between the transmissions.
- We calculate the packet error rate (PER) as a function of the BER.

Analytical estimation enables us to calculate the PER caused by interference according to the spatial and channel distances between the parallel transmissions. We verify the estimation method with the experiments and successively use the results to simulate the interference behavior in larger networks.

A. SIR Calculation

We first calculate the received signal strength at the receiver. The distances between the nodes are translated into signal loss (attenuation) using a path loss model. In particular we use an exponential path loss formula given in Equation 1:

$$L_{dB} = 10log\left(\frac{P_t}{P_r}\right) = 10log\left(\frac{4\Pi d}{\lambda}\right)^{\alpha} \quad (1)$$

where L_{dB} represents the loss in dB, P_t and and P_r are the transmitted power and the received power respectively. d is the physical distance between the transmitter and the receiver, λ is the carrier wavelength and α is the path loss factor.

It can be argued that the mentioned path loss model may be inadequate to predict the signal loss. First, we note that our main focus is not modeling the signal propagation but modeling the inter-channel interference. We are interested in the differences between the signal levels of the simultaneous transmitters. Next, the behavior of example platform has been experimented in an indoor-corridor environment and found to be similar with the calculated signal power [14].

According to the transmission power of the transmitter and the loss in terms of the distance between the nodes, we can calculate the received signal power. Similarly, given the transmission power of the jammer and the distance to the affected receiver, we can calculate the level of interference at the receiver. The signal to interference ratio (SIR) is given as follows:

$$SIR = [P_t - L(d_t)] - [P_j - L(d_j)] \quad (2)$$

where P_j is the transmission power of the jammer, d_t and d_j are the distance between the transmitter and receiver, the distance between the jammer and the affected receiver, respectively.

There are several factors that can influence the received signal strength: the orientation of the antennas, environmental effects such as multi-path effect, etc. In order to take those effects into account we assume that the SIR may differ (+,-)10dB from the calculated value according to a normal distribution. 10dB of variance is a measured average value for our example platform in an indoor environment. One can change these values for a different platform or environmental characteristics. Variation of SIR is presented in Figure 3. The calculated SIR value is shown as 0dB and the SIR can take values between -10dB and $+10$dB, according to normal distribution.

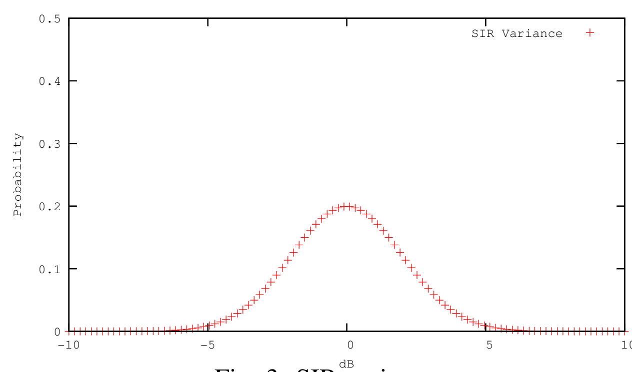

Fig. 3: SIR variance

B. BER calculation

Given the SIR values, we can predict whether the receiver can demodulate the target modulated signal according to the "co-channel rejection" and "blocking" parameters. Co-channel rejection is a measure of the receiver's capability to demodulate a target signal in the presence of an unwanted signal, if both signals are on the frequency of the receiver [15]. Blocking indicates how much power the receiver can tolerate on a nearby frequency/channel, and still can receive on a desired channel. It is the lower bound for the difference between the signal powers at the receiver. The example platform used during the experiments has a co-channel rejection of 13dB. This means if the wanted signal is 13dB or higher in magnitude than the unwanted signal, correct demodulation is performed. Correct demodulation typically means a BER smaller than 10^{-3}. The blocking values of the transceiver are given as follows: 1st adjacent channel (200kHz): -7dB, 2nd adjacent channel (400kHz): -16dB, $+1$MHz: -40dB, -1MHz:

-50dB, -2MHz: -63dB, $+5$MHz: -70dB, -5MHz: -65dB, $+10$MHz: -69dB, -10MHz: -67dB.

As we mentioned, we assume that the SIR might vary $-10, +10$ dB from the calculated SIR value. We calculate the probability that the SIR value is below the blocking value for a given channel spacing. The probability value gives us the BER according to the channel spacing between the nodes. If the SIR is higher than the blocking threshold, the bits can be modulated. For example, if the SIR value is calculated as -50dB, we assume the SIR may vary between -40dB and -60dB. If the jammer operates on the adjacent channel, then the receiver cannot receive since the SIR is less than -7dB. If the SIR is below this value, the receiver cannot interpret the signal from the transmitter. However, if the channel distance between the jammer is 10 (2MHz, blocking:-63dB), then the SIR is higher than the blocking value and the BER is 0; if the channel distance is -5 (-1MHz), the blocking value is -50. So we calculate the probability, BER, that the SIR is between -60 and -50.

C. PER Calculation

In the next step, we calculate the PER as a function of the BER. The probability of not having a bit error is the probability that all the bits are received correctly. Therefore the conditional probability of PER is one minus the the probability of no bit errors. PER is computed as follows:

$$PER = 1 - (1 - BER)^N \qquad (3)$$

where N represents the number of bits in a packet. For the experimental setting each packet is composed of 256 bits. If there is an error correction mechanism, then the PER utilizing the BER should be computed differently. However, the experimental platform does not provide an error correction mechanism. Equation 3 is the final form of the PER.

D. Multiple jammers

The number of simultaneous transmissions in the environment is another important factor which affect the level of interference. In the preceding sections we calculate the BER in the presence of a single jammer. In the case of multiple jammers, which is more likely to occur in a large set of nodes, a wireless signal is decoded by treating the sum of all the other transmissions as noise. The SIR in the presence of multiple jammers is calculated as follows:

$$SIR = (P_t - L(d_t)) - \sum (P_j - L(d_j)) \qquad (4)$$

The rest of the calculations for BER and PER are performed the same as in the case of a single jammer.

IV. Evaluation with the Experimental Results

As we mentioned in the introduction, unrealistic/idealistic models may not always be reliable to estimate the real performance of wireless networks and should be tested with experimentation. In this section we present the comparisons of the analytical estimation and the experiments.

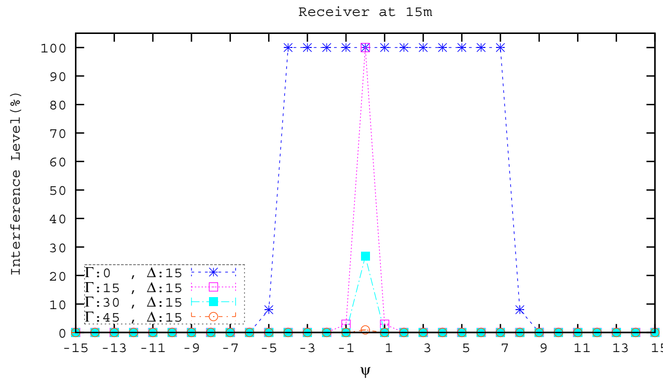

Fig. 4: Calculated PER versus channel spacing

The comparisons are based on a binary matching. If the PER according to a given channel spacing is larger than 0, then we consider it as 1 which indicates that there is interference. Otherwise, there is no interference effect (0). For different positions of the jammer that are mentioned in Section II and different channel spacings we repeat the same process. Finally, we compute in how many cases the experimented and calculated results are the same i.e., can estimate the PER same, either 0 or 1. Figure 4 presents the analytical results for an example setting, whereas Figure 2 shows the experimented results for the same set. The x-axis (Ψ) shows the channel spacing between the transmitter and the jammer. Different lines stand for different values of Γ, the physical distance between the jammer and the receiver.

The comparisons are given in Tables I and II. Topology and abbreviations are the same as in Figure 1 (J:Jammer, R:Receiver). The average matching is found to be 90% in the case of a single jammer and 87% for multiple jammers between the experimental and analytical results. This shows that, the analytical estimation can capture the experimented level of interference at an acceptable level. As we emphasized before, supporting analytical models by experiments is important before generalizing the results by simulations to overcome the mistakes caused by unrealistic assumptions.

	R1 @ 30m.	R2 @ 45m.	R3 @ 60m.	R4 @ 75m.
J @ 0m	96.8	96.8	90.3	96.8
J @ 15m	100	100	100	100
J @ 30m	87.1	96.8	100	83.9
J @ 45m	93.5	67.7	93.5	71.7
J @ 60m	96.8	93.5	74.2	64.5
J @ 75m	100	90.3	80.6	100

TABLE I: Ratio of matching between calculated and experimented results

V. Capacity Estimation Simulations

We have investigated the individual node packet-loss/delivery capacities by experimental measurements. Based on the analytical interference estimation method, we develop a simulation model in Matlab to analyze the overall capacity of the network in terms of orthogonal channels and overlapping channels in a larger setting.

	R1 @ 30m.	R2 @ 45m.	R3 @ 60m.	R4 @ 75m.
J @ 15m	73.1	66.6	69.8	33.3
J @ 30m	73.1	90.5	96.8	93.6
J @ 45m	95.2	88.8	98.4	96.8
J @ 60m	96.8	95.2	100	87.3
J @ 75m	93.6	96.8	96.8	100

TABLE II: Ratio of matching between calculated and experimented results (multiple jammers)

A topology generator is used to randomly distribute the nodes within the terrain according to a uniform distribution. We have created 5000 random topologies. We run the simulation for each topology with overlapping channels and discrete[1] channels. We vary different parameters: the number of nodes, number of channels, transmission power and terrain dimensions.

A destination node is selected for each node and the signal strength at the destination is calculated. According to the analytical estimation, the interference among simultaneous transmissions is computed. A channel is assigned to a node if the PER due to interference is 0 and if the destination is not addressed by another node. We define the capacity as the number of nodes that can successfully be assigned a channel and can access the media. If the usage of orthogonal channels are assumed, a node checks the interference level on the same channel. On the other hand, if the interfering channels are considered, then a node has to check all the interference levels also on the adjacent channels.

A. Capacity with Overlapping Channels and Orthogonal Channels

In the first set of the experiments we analyze the capacity with the usage of overlapping channels and using only the orthogonal channels. In this setting, the transmission power is set to 10dBm and the terrain dimensions are 100*100m^2.

As we mentioned, the transceiver provides 512 channels with 200kHz channel width. According to the experimental values and the data sheet of the example platform, channel spacing should be 50MHz (channel spacing should be 50) to guarantee interference-free communication. Considering this, we compare the performance with 10 orthogonal channels and 512 overlapping channels. Both the overlapping channels and orthogonal channels occupy the same spectrum between 868-915 MHz. Figure 5 presents the results. The x-axis shows the number of nodes and the y-axis shows the ratio of the nodes that can simultaneously access the media.

If the transceiver operates on a single channel, very limited number of nodes can simultaneously communicate. As the number of nodes increases, the density increases and this results in less chance to access the media due to higher interference and contention. If the nodes use only orthogonal channels, the performance is pessimistic in the sense that two nearby communications can simultaneously take place on closer channels if the interference level is tolerable. If the nodes use overlapping channels by controlling the interference at an acceptable level the number of simultaneous transmissions is significantly increased: in the example simulations all the nodes can communicate even if the network gets denser. Increasing the number of simultaneous transmissions improves the network performance by increasing the throughput [16] and reducing the medium access and communication delay.

[1]Discrete and orthogonal channels are used interchangeably in the text.

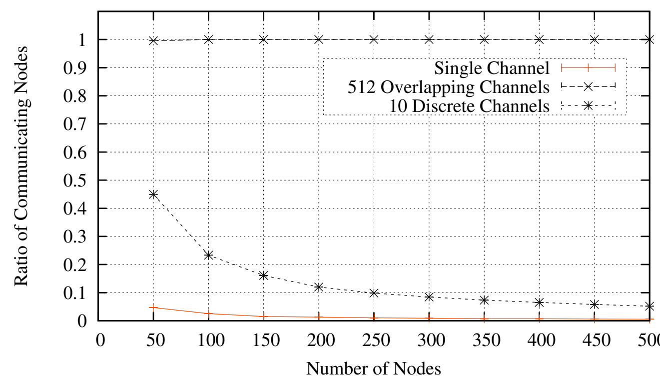

Fig. 5: Capacity with Overlapping Channels (512) versus Discrete Channels (10)

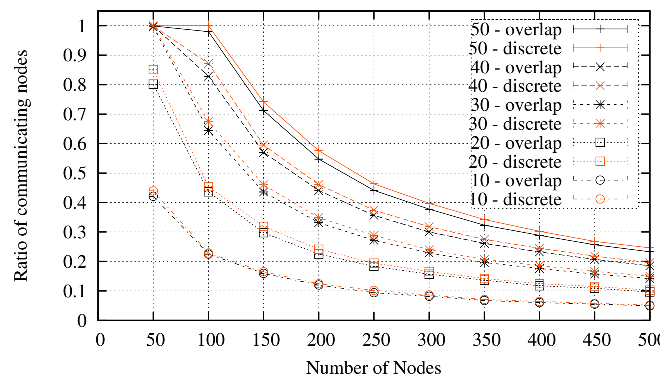

Fig. 6: Capacity with the Same Number of Overlapping and Discrete Channels

B. Capacity with the Same Number of Overlapping Channels and Orthogonal Channels

In the first set of the experiments, the capacity increase was inevitable since the network can make use of more channels. In this set, we analyze the capacity with the same number of orthogonal and overlapping channels. Orthogonal channels constitute a wider spectrum. For instance 10 orthogonal channels require 500MHz-wide band whereas 10 overlapping channels make up a 2MHz-wide band.

Figure 6 shows the ratio of communicating nodes as a function of the number of channels. Terrain dimensions and the transmission power parameters have the same values as in the previous set. The capacity results of the discrete channels are on the average 1-3% better than the results of the overlapping channels. The small difference is due to the fact that the ratio of the nodes that create adjacent channel interference over the nodes that create co-channel interference is quite small.

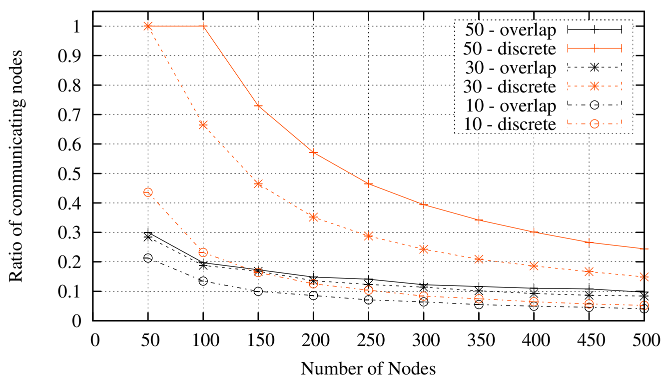

Fig. 7: Impact of Blocking Values on the Capacity

Therefore, the adjacent channel interference does hardly affect the achievable capacity.

The careful use of interfering channels provides better utilization of the spectrum. Although the overlapping channels span a narrow band of the spectrum, the achievable capacity is similar to the capacity with orthogonal channels which constitute a wider band. By careful analysis of interference in terms of distance, transmission power, etc. the transmitters can be assigned channels with less spacing. This allows the use of much more channels over a given band.

C. Impact of Transceiver Characteristics

In this set of the simulations, we discuss the impact of blocking values on the capacity. The default interference blocking value of the transceiver for the 1st adjacent channel (200kHz) is -7dB. This means if there is a jammer operating on the 1st adjacent channel, the signal from the jammer can be maximum 7dB stronger than the signal power of the transmitter on the same channel for none-interfering communication. If we decrease the default interference blocking values then a receiver will be more prone to the interference from adjacent channels.

Figure 7 shows the capacity results when the interference blocking values are reduced by a factor of 10. The results for the discrete channels is the same as the results of the default values shown in Figure 6. When overlapping channels are considered, the capacity values differ. We achieve lower capacity since the impact of the nodes in the adjacent channel interference region is much higher. The receivers are more prone to the interference created by those nodes. The difference of the capacity between overlapping channels and discrete channels reaches a factor of 0.7 with 50 channels. However, when the number of nodes increases, then the capacity values tend to be similar. This is due to the fact that the major limiting factor on the achievable capacity is the number of channels.

The results of the simulations show that adjacent channel interference has an impact on the capacity if the transceiver is prone to the adjacent channel interference. This should not be ignored when developing realistic protocols and algorithms on multi-channel wireless networks. However if interference blocking values of the transmitters are firm enough against the adjacent channel interference, the achievable overall network capacity does not significantly differ from the capacity of orthogonal channels.

D. Correctness of Orthogonal Channels Assumption

As we mentioned, one of the general assumptions in multi-channel protocols is the perfect orthogonality of the channels. In this section, we investigate the correctness of this assumption. In particular, we investigate what if we treat the overlapping channels as orthogonal. In the simulations, we assume n number of orthogonal channels that constitute the same band as the overlapping channels. We investigate how many nodes are scheduled incorrectly. This means incorrectly scheduled nodes select a channel according to the orthogonality assumption by only checking the interference on the selected channel. However, interference from the simultaneous transmissions on nearby channels may still disturb the transmission. Figure 8 presents the results. The y-axis shows the ratio of the nodes that are incorrectly scheduled for transmission over the total number of nodes. Error rate is much higher in sparser scenarios and decreases with the density since the ratio of simultaneous transmissions (ratio of communicating nodes) decreases. Although the capacity with orthogonal channels and overlapping channels is observed to be the same (SectionV-B), we cannot treat the channels as orthogonal and the channel selection by the orthogonality assumption may not always be correct. Furthermore, the protocols based on the orthogonal channels assumption may fail in a practical setting.

VI. Conclusions

We have presented a methodology that experimentally characterizes the multi-channel interference and analytically estimates the interference based on the observations from the experiments. Furthermore, we have shown how the estimation methodology can be used at deriving estimates of the performance metrics of a larger network by simulations. Simulation results support the previous conclusion on the use of overlapping channels: the overall network capacity significantly increases with the use of overlapping channels. When we investigate the impact of orthogonality, we observe that the overall network capacity by using overlapping channels is

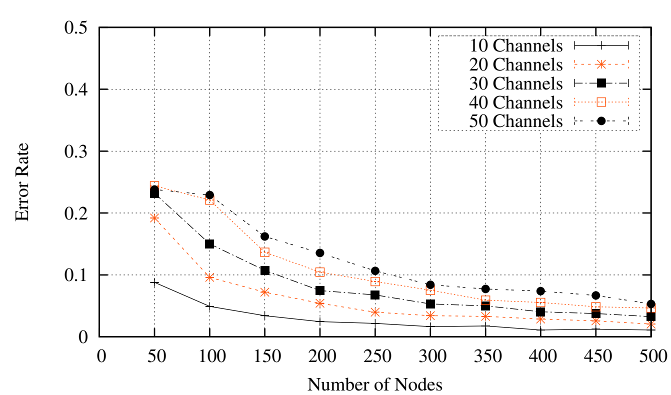

Fig. 8: Incorrectness of Discrete Channels Assumption

close to the capacity of orthogonal channels, depending how much the receiver is prone to the interference. This shows that overlapping channels which constitute a much smaller band, provides more efficient use of the spectrum. If overlapping channels are assigned carefully in the same spatial domain, the spectrum is utilized more efficiently compared with the use of only orthogonal channels. In the last set of the simulations, we explore the assumption of treating the channels as orthogonal. Simulations results show that the transmission schedules based on orthogonal channel assumption is not always correct.

As a future work, we plan to investigate the effects of our findings on the performance of channel assignment and MAC algorithms which considered only the use of interference-free channels.

VII. Acknowledgments

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