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Study and Analysis of Characterizing the Capacity of Wireless Ad Hoc Networks

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ABSTRACT: **This paper provides an overview of metrics for capacity evaluation of Ad hoc wireless networks. The capacity metrics based on statistical approach incorporate aspect from the physical layer and from the network layer. These metrics are suitable for network design and parameter optimization. Whereas the capacity metrics based on network scalability describe how network capacity behaves when the number of nodes in the network grows. Therefore even though the scaling laws are rather pessimistic, it can be used to design of more appropriate transmission schemes. A set of simple powerful tool is applied to quickly determine the capacity scaling laws for various physical layer technologies under the protocol model.**

Keywords: Expected forward progress, Information efficiency, Transmission capacity, Aggregate multi-hop information efficiency, Transport capacity, the protocol interference model, the physical interference model etc.

I. INTRODUCTION

For the modelling and measuring the capacity of ad hoc networks [1], a large number of metrics have been proposed for characterizing the capacity of ad hoc networks under different conditions and emphasizing different aspects of the network. The investigation of the relationship between capacity and transmission radius in a network of packet radios operating under ALOHA protocol are based on the metric called expected forward progress, defined such way to capture the trade off relating the one-hop throughput and the average one-hop length [2]. Decreasing one-hop length may increase throughput due to link quality improvement and also may decrease throughput due to a larger traffic and a higher contention level caused by consequent larger number of hops between source and destination [3]. The concept of information efficiency defined as the product of the expected forward progress and the spectral efficiency of the transmission systems takes into account of channel reuse and multi-hop transmissions leading to new metric, named aggregate multi-hop information efficiency [4]. Based on a similar concept of information efficiency, the metric transmission capacity is related to the optimum density of concurrent transmissions. Transmission capacity is the area spectral efficiency of successful transmissions from the optimal contention density [5]. The transmission capacity metrics have in common their statistical nature of several mechanisms related to wireless communications, such as the interaction among nodes sharing a given channel and the propagation effects.

Based on a deterministic approach to characterize the capacity of ad hoc networks and on the behaviour of capacity scaling laws, the concept of transport capacity relates transmission rate and source-destination distance [6]. The formulation of transport capacity from the perspective of the requirements for successful transmission is described according to two interference models: the protocol interference model, which is geometric based, and the physical interference model, based on signal-to-interference ratio requirements [7]. When the number of nodes grows, the behaviour of network capacity show that the per-node throughput decreases as O $(1/\sqrt{n})$, when n is the number of nodes in the network [8]. Section II provides an overview of capacity metrics for wireless ad hoc networks. Section III explains how the transport and throughput capacity work under protocol and physical interference model for capacity scaling laws. Section IV anal sizes the characterization of capacity improvements. Section V simulates the capacity improvements results and at last Section VI concludes the paper and followed by the references.

II. STATISTICAL BASED CAPACITY METRICS

The inherent random nature of ad hoc networks suggests a statistical approach to quantify capacity of such networks. A Statistical approach is very useful for the design of practical communication systems, when a set of quality requirements is imposed by the user application. Some statistical-based capacity metrics, namely expected forward progress, information efficiency, transmission capacity and aggregate multi-hop information efficiency metrics are discussed in this chapter.

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A. Expected Forward Progress

Expected forward progress (EFP) is measured in meters and is defined as the product of the distance travelled by a packet toward its destination and the probability that such packet is successfully received.

$$EFP = d \times (1 - P_{out}) \quad (1)$$

Where d is the transmitter-receiver separation distance and *Pout* is the outage probability i.e., the probability that the bit error rate is higher than a given threshold.

B. Information Efficiency

Information efficiency is defined as the product of Expected forward progress (EFP) and spectral efficiency η of the link connecting transmitter and receiver nodes,

$$IE = \eta \times d \times (1 - P_{out}) \quad (2)$$

IE quantifies how efficiently the information bits can travel towards its destination. To capture the trade off by the information efficiency, a transmission system in which modulation and error correcting coding techniques will be selected to optimize the IE of the network. If a modulation technique with large cardinality is used, then the spectral efficiency of the system increases, at a higher minimum required signal-to-interference plus noise ratio (SINR) to achieve a given packet error probability. This higher required SINR increases the outage probability Pout. Error correcting coding techniques reduces minimum required SINR at the higher bandwidth, reducing therefore the spectral efficiency of the transmissions. These trade off are captured by the information efficiency metric, allowing for a joint system design involving modulation, coding, transmission range, among other parameters [10].

C. Transmission Capacity

Transmission capacity (TmC) metric single-hop ad hoc networks is defined as the product of the density of successful links and their communication rates, subject to a constraint on the outage probability [11].

$$TmC = \eta \times \lambda \times (1 - P_{out}) \quad (3)$$

Where λ is the density of active links in the network. TmC quantifies the spatial spectral efficiency of the network, capturing in its formulation the effects of active links density on the outage probability. With a high density of concurrent transmissions, information flow in the network is also higher indicated by a high TmC. However the downside of a high density of active links is an increase in the interference level, leading to a higher outage probability and a lower transmission capacity.

D. Aggregate Multi-hop Information Efficiency

Aggregate Information Efficiency (AIE) is defined as the sum of Information Efficiency (IE) of active links in the network per unit area [9]. Aggregate Multi-hop Information Efficiency (AMIE) is to abstract multi-hop links and evaluate AMIE based on end-to-end performance of multi-hop links.

$$AMIE = d \times \eta \times \lambda \times (1 - P_{out})^h \quad (4)$$

Where h is the average number of hops between source and destination. The main advantage of AMIE is to be more flexible and general than other similar metrics.

III. CAPACITY SCALING LAWS

Capacity scaling laws of wireless networks is defined how capacity scales as the number of nodes in the network grows [12]. This is an important prospect to investigate how several intrinsic aspects of wireless communication such as interference, channel reuse and resource limitation affects the performance of the network. Throughput, measured in bits per second, is a metric of capacity of communication networks. In ad hoc networks, source and destination nodes may be far apart, such that direct communication (single hop) is not possible, requiring a multi-hop connection, with neighbouring nodes acting as relays. Multi-hop connection leads to a traffic increase, as a given packet is transmitted several times before reaching its final destination. Therefore, source-destination separation distance must be taken into account when characterizing capacity in wireless ad hoc networks. To do so, Transport Capacity, measured in bit-meter per second is used. By considering a network with transport capacity of T bit-meter per second, the rate between two nodes spaced one meter away from each other is T b/s. If the distance between the nodes is doubled, the rate decreases to *T/2 b/s.*

A. Transport Capacity under the Protocol Interference Model

A network of n immobile nodes, which can act simultaneously as source, relay or destination is considered. These n nodes are arbitrarily located in a planar disk of unity area. The positions of the nodes can be adjusted to satisfy the conditions for successful transmissions imposed by interference model [13]. Every node selects randomly another node as the destination of its bits.

Transport capacity T_A of an arbitrary network with n nodes under the protocol model,

$$TA = \Theta (W \sqrt{n}) \text{ bit. meter/s} \quad (5)$$

This means that the transport capacity per node is $\Theta (W \sqrt{1/n})$ bit. meter/s and goes to zero as the number of nodes increases.

Under the protocol reference model, disks of radius equals to $\Delta |X_i - X_{R(i)}|/2$ centered at receiver nodes of

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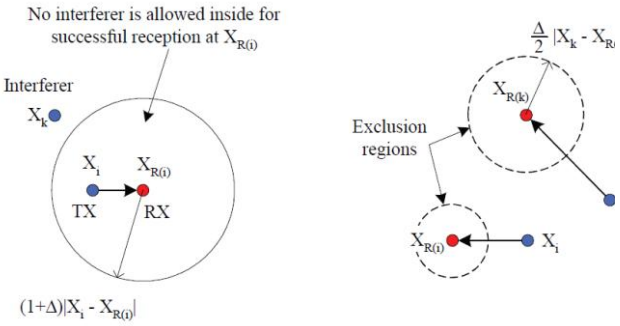
successful links are disjoint as shown in **Fig.(1(a))** and **Fig.(1(b))**.



(a) **(b)**

Fig (1). The protocol model: **(a)** Disk around receiver $X_{R(i)}$ must be free of interfering nodes for correct reception at node $X_{R(i)}$; **(b)** Two links are successful if the corresponding exclusion regions are disjoint.

Each successful link consumes a fraction of network area and the sum of area of disks of all successful links is upper limited by the network area. Neglecting the border effects (i.e. when nodes are close to the boundary of network area) as shown in **Fig. (2).**

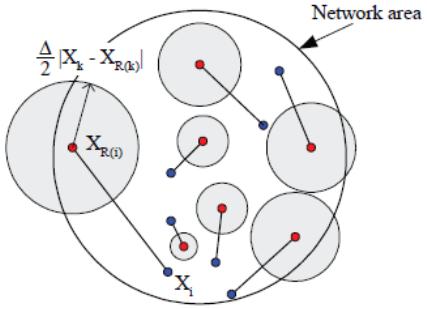


Fig. (2). Arbitrary network under the protocol interference model: successful links correspond to disjoint disks.

$$\sum_{i\in T(t)} \pi \left(\frac{\Delta}{2} d_i\right)^2 \leq 1 \rightarrow \sum_{i\in T(t)} d_i \leq \frac{4}{\pi\Delta^2} \qquad (6)$$

Where d_i is the T-R separation distance $|Xi - X_{R(i)}|$of the *i*-th T-R pair, and T(t) is the set of successful links at time t.

By assuming that all sources transmitting at rate W, the transport capacity T_A of the network at a given time t in upper bound,

$$T_A = W \sum_{i\in T(t)} d_i \leq \sqrt{\frac{2}{\pi}} \frac{W}{\Delta} \sqrt{n} \qquad (7)$$

Or, $T_A = O\left(W\sqrt{n}\right)$ bit-meter/s (8)

B. *Transport Capacity under the Physical Interference Model*

The transport capacity under the physical interference model,

$$T_A = O\left(W n^{\frac{\alpha-1}{\alpha}}\right) \text{ bit-meter/s} \qquad (9)$$

If all sources transmitting at rate W, the transport capacity in upper bound,

$$T_A = W \sum_{i\in T} d_i \leq \frac{W}{\sqrt{\pi}} \left(\frac{2\beta+2}{\beta}\right)^{1/\alpha} n^{\frac{\alpha-1}{\alpha}} \qquad (10)$$

If the capacity is equitably shared among all sources, the transport capacity per node is,

$$T_A = O\left(W/n^{1/\alpha}\right) \qquad (11)$$

And it goes to zero as *n* increases. This upper bound indicates that a larger path loss exponent α leads to a higher capacity. Therefore a larger α means stronger signal attenuation and reduced interference.

C. *Throughput Capacity under the Protocol Interference Model*

Throughput capacity in bits per second of a random network under the protocol interference model in upper bound,

$$\lambda(n) \leq \frac{c\,W}{\sqrt{n\,\log n}} \qquad (12)$$

Now, a network with *n* nodes randomly placed on a disk of unity area and all nodes transmitting with a common transmission range r_n is considered. In order to make sure that no node is isolated in the network, r_n must be larger than $\sqrt{\log n/\pi n}$. Under the protocol interference model, successful transmissions require that disks of radius $\Delta r_n/2$, centered at receivers, must be disjoint, as shown in **Fig.(3).**

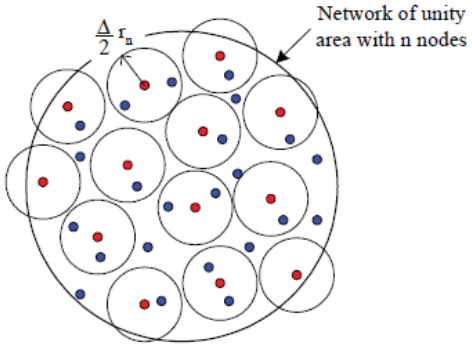


Fig. (3). The protocol model: Disks around active receivers must be disjoint.

Therefore, the number of successful transmissions *Ns* within a disk of unity area in upper bound,

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$$N_s < \frac{4}{\pi\Delta^2 {r_n}^2} \quad (13)$$

Therefore, the aggregate number of bits transmitted per second in the network cannot be larger than

$$\frac{4W}{\pi\Delta^2 {r_n}^2} \quad (14)$$

separation distance. $\bar{L}$ does not depend on the number of nodes in the network. Therefore, the average number of hops between source and destination in lower bound as shown in **Fig. (4).**

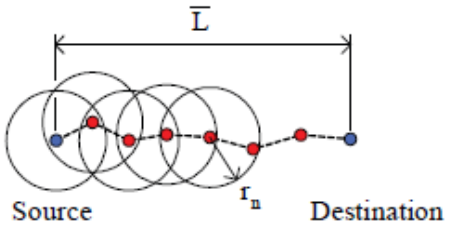

Fig. (4).The protocol model: average number of hops between source and destination.

If each source generates bits at rate $\lambda(n)$, then the average number of bits transmitted by $n\,\lambda(n)\bar{L}/r_n$ and must satisfy

$$n\,\lambda(n)\frac{\bar{L}}{r_n} \leq \frac{4W}{\pi\Delta^2 {r_n}^2} \quad (15)$$

Finally, under the protocol interference model, throughput capacity per bits per second,

$$\lambda(n) \leq \frac{c\,W}{(1+\Delta)^2\sqrt{n}\log n} \quad (16)$$

The order of throughput capacity of random networks under the protocol interference model,

$$\lambda(n) = \Theta(W/\sqrt{n}\log n) \quad (17)$$

D. Throughput Capacity under the Physical Interference Model

An upper bound on the throughput for random network under the physical interference model can be derived using the upper bound on the throughput for the case under the protocol interference model. Successful links (X_i, $X_{R(i)}$) in a random network under the physical interference model are also useful under the protocol interference model, for appropriate values of Δ and β. Therefore, an upper bound on the throughput for the protocol model also holds for the physical model. Therefore, for a random network under the physical interference model the throughput in upper bound,

$$\lambda(n) < \frac{c\,W}{\sqrt{n}} \quad (18)$$

IV. ANALYSIS OF CHARACTERIZING THE CAPACITY

When a wireless network uses more channel resources for transmissions, it should achieve a proportionality higher network capacity. If an IEEE 802.11 ad hoc network can achieve capacity C using a single channel, the targeted capacity using n channels should be $n.C$. It integrates two algorithms: 1) a link-directionality – based dual – channel medium – access – control (MAC) protocol (DCP) and 2) a signal- to- interference ratio (SIR) comparison algorithm (SCA). When combined, these two algorithms compensate for the shortcomings of the other to achieve superior performance in a wide range of situations.

The capacity characterization of the DCP, the SCA, and the proposed protocol (the DCPwSCA) are analyzed and the upper capacity bounds of the proposed DCPwSCA, the DCP and the SCA are calculated first and then the maximum achievable capacity of an ad hoc network using the original 802.11 protocol in the same given network area is considered. Finally their characterization of capacity improvements is compared. Given a network in a large area S, the upper capacity bound is the maximum number of simultaneous transmission links that can be packed in area S.

A. Upper Capacity Bound of the DCPwSCA

To calculate the upper bound on the throughput capacity, the exclusion region consumed by each transmission link is identified [14]. An exclusion region is a region around each receiver such that no interferer/transmitter exists inside this region [15]. In this protocol (DCPwSCA), link i can successfully transmit if one of the two nodes of link j is outside the interference range (In Range) of link i. The interference range of link I,

$$In\ Range_i = (1+\Delta)\,r_i \quad (19)$$

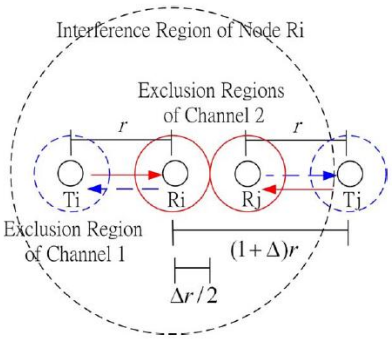

Fig. (5). Exclusion regions of a pair of simultaneous-transmission links using the DCPwSCA.

Where r_i is the transmitter-receiver distance of link i, and Δ > 0 is related to a power margin. **Fig. (5)** shows an exclusion regions of a pair of simultaneous- transmission links

Where W is the common transmission rate of the individual transmissions.

It is considered that source nodes choose their destination nodes randomly and denote $\bar{L}$ the average source-destination

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using the DCPwSCA when links *i* and *j* are packed with the closest distance. Since node T_i (T_j) of link *i (j)* is outside the In Range of *Rj (Ri)*, links i and j can transmit concurrently. The distance between R_i and R_j is equal to Δr. Thus the exclusive region of each channel of a link is a circular disk of radius Δr/2 that is centered at the receiver of each channel of the link. For simplicity, a network of area S with all links having the same transmitter-receiver length r, and the total data rate using all channels W are considered. The area of the exclusion region of each channel of a link using DCPwSCA,

$$E_{\text{DCPwSCA}}, = \frac{\pi \Delta^2 r^2}{4} \quad (20)$$

Due to the bidirectional traffic of each link, the upper bound of the throughput capacity per channel,

$$C_{\text{DCPwSCA}} = \frac{W}{2} \cdot \frac{S}{E_{DCPwSCA}} = \text{W} \frac{2S}{\pi \Delta^2 r^2} \quad (21)$$

Thus C_{DCPwSCA} depends on the transmitter – receiver distance of a link (*r*) only.

B. *Upper Capacity Bound of the DCP*

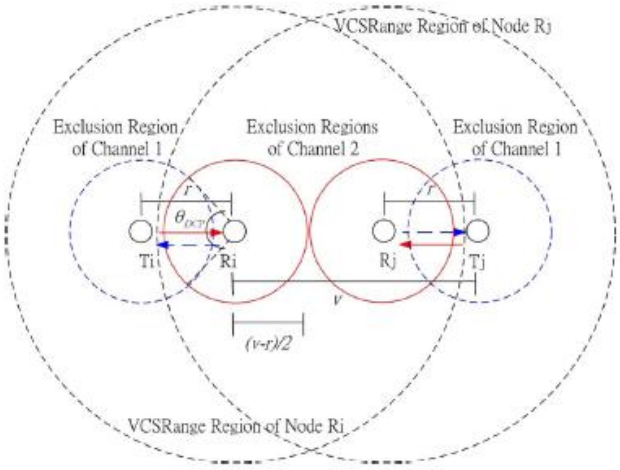

Fig. (6). Exclusion regions of a pair of simultaneous-transmission links using the DCP.

In the DCP, simultaneous transmissions are allowed if one of the two nodes of link *j* is outside the *VCSRange* of either the transmitter or the receiver of the link *i*. Fig. (6) shows that since node *Ti (Tj)* of link *i (j)* is outside the *VCSRange* of *Rj (Ri)*, links i and j can transmit at the same time. When links *i* and *j* are packed with the closest distance, the distance between *Ri* and *Rj* becomes *v-r*. Since the transmitter and receiver of a link use different channels for receptions, the exclusion region of each channel of a link is a circular disk of radius *v – r/2* that is centered at the receiver of each channel of the link. The area of the exclusion region of each channel of a link using the DCP,

$$E_{DCP} = \frac{\pi (v-r)^2}{4} \quad (22)$$

The DCP uses two channels for the bidirectional traffic: RTS/DATA in one channel and CTS/ACK in another. The upper bound of the throughput capacity per channel,

$$C_{DCP} = \frac{W}{2} \cdot \frac{S}{E_{DCP}} = \text{W} \frac{2S}{\pi (v-r)^2} \quad (23)$$

C. *Upper Capacity Bound of the SCA only (Without the DCP)*

For comparing the capacity enhancements that are obtained by splitting channels based on link directionalities (DCP) and adopting SCA in the protocol, the exclusion region of a single channel protocol with SCA (without DCP) is derived. Since only one channel is used by the protocol, simultaneous transmissions of links *i* and *j* are permitted only

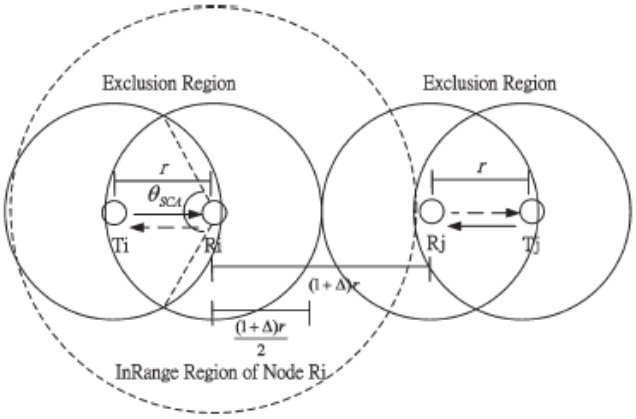

Fig. (7). Exclusion regions of a pair of simultaneous-transmission links using the SCA only (without the DCP).

If *Ri* and *Ti* are outside the interference range *In Range* of *Ri* and *Tj* as shown in **Fig. (7)**. Thus the exclusion region of each link becomes two disks of radius (1 + Δ) r / 2 centered at two nodes of the link. To calculate the area of the exclusion region of a link, angle θ_{SCA} is derived as shown in **Fig. (7)**.

$$cos\left(\frac{\theta_{SCA}}{2}\right) = \frac{r}{2\,(1+\Delta)r/2} = \frac{1}{1+\Delta}$$

$$\theta_{SCA} = 2\cos^{-1}\left(\frac{1}{1+\Delta}\right) \quad (24)$$

The area of the exclusion of a link using SCA,

$$E_{SCA} = \frac{\pi\,(1+\Delta)^2 r^2}{2} - \left(\frac{(1+\Delta)^2 r^2}{4}\,\theta_{SCA} - r.\frac{(1+\Delta)\,r}{2}.\sin\frac{\theta_{SCA}}{2}\right) \quad (25)$$

and the upper bound of the capacity,

$$C_{SCA} = \text{W} \frac{S}{E_{SCA}} \quad (26)$$

D. *Upper Capacity Bound of the Original 802.11 Protocol*

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To calculate the upper capacity bound of the network using the original 802.11 protocol, the exclusion region consumed by each link is identified [16]. **Fig. (8)** shows a pair of links that can transmit simultaneously. Nodes *Ri* and *Rj* of links *i* and *j*, respectively, are located just outside the *VCSRanges* of the other link. Ri and Rj cannot sense the signals from each other, and thus, they can transmit at the same time. In the original 802.11 protocol, Ri and Rj have to reply ACKs back to the transmitters Ti and Tj. When ACK is transmitting, Ri (Rj) becomes a transmitter, while Ti (Tj) becomes a receiver.

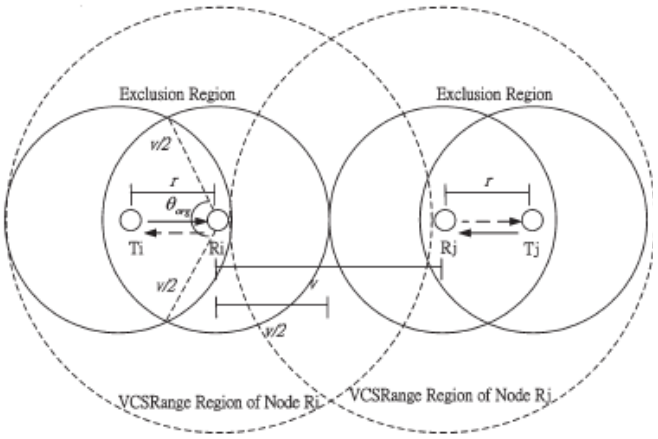

Fig. (8). Exclusion regions of a pair of simultaneous-transmission links using the original 802.11 Protocol.

This bidirectional traffic of the original 802.11 protocol further enlarges the exclusion region that is consumed by each link. As shown in **Fig. (8)**, the exclusion region is defined as two disks of radius *v/2* centered at two nodes of a link, where *v* is the virtual carrier- sensing range (*VCSRange*). Once the exclusion regions of links are disjointed, simultaneous transmissions are permitted by the protocol. To calculate the area of the exclusion region of a link, the angle θ_{org} is derived as shown in Fig. (8).

$$\text{Cos}\left(\frac{\theta_{org}}{2}\right) = \frac{r}{2\,(v/2)} = \frac{r}{v}$$

$$\theta_{org} = 2\cos^{-1}\left(\frac{r}{v}\right) \qquad (27)$$

Thus, the area of the exclusion region of a link using original 802.11 protocol,

$$E_{org} = \frac{\pi\, v^2}{2} - \left(\frac{v^2}{4}\theta_{org} - r.\frac{v}{2}.\sin\frac{\theta_{org}}{2}\right) \qquad (28)$$

The upper bound of the throughput capacity,

$$C_{org} = \text{W}\,\frac{S}{E_{org}} \qquad (29)$$

Thus C_{org} depends on the *VCSRange* *v* and the transmitter-reciever distance *r*.

E. *Comparisons*

The areas of the exclusion region of a link using the original 802.11 protocol and the DCP depends on the *VCSRange* *v* and the transmitter-receiver distance *r*, whereas those links using the DCPwSCA protocol and the SCA are deteremined only by *r* and are independent of *v*. The capacity improvement of DCPwSCA by comparing with the original 802.11 protocol is,

$$I_{DCPwSCA\,(r)} = \frac{C_{DCPwSCA\ (r)}}{C_{org\,(r)}} = 2.\frac{E_{org}}{\pi\,\Delta^2\,r^2} \qquad (30)$$

The assumed constant link length in the network from r_{max} to r_{min} is varied. The average capacity improvements,

$$I_{DCPwSCA\,(r)} = \frac{1}{r\_max\ -r\_min}\int_{r\_min}^{r\_max}\frac{2.E_{org\,(r)}}{\pi\,\Delta^2\,r^2}\,dr \qquad (31)$$

The capacity improvements are obtained by two factors:

1) Permitting closer packing of simultaneous transmissions by splitting the reception channels of nodes of each link (by the DCP);
2) Releasing the protocol constraints that are induced by the virtual carrier-sensing mechanism (by the SCA);

For factor 1, the DCPwSCA seperates the transmission and reception channels of a node. This allows nodes using the same reception channel to be packed closer to each other since their transmissions use another independent channel that does not interfere with the receptions of the other link. For factor 2, both the 802.11 and the DCP relay on their carrier-sensing conditions to justify their transmission processes. The DCPwSCA bases on its SCA instead of the virtual carrier-sensing mechanism to seek simultaneous transmission opportunities. This, again, allows simultaneous transmissions to be packed closer to each other with interlink distances that are less than the *VCSRange*.

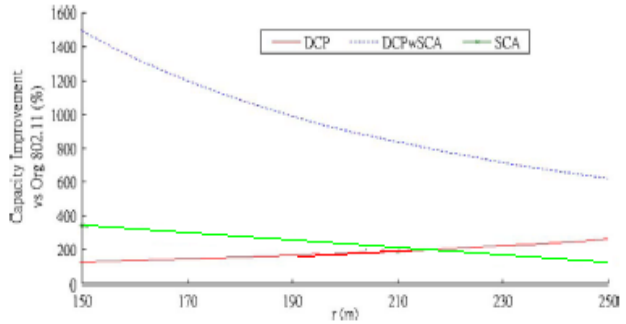

Fig. (9). Theoretical capacity improvements of protocols against the original 802.11 protocol versus the transmitter-receiver distance r.

Fig. (9) shows the capacity improvements that are obtained by the DCPwSCA ($I_{DCPwSCA}$ (r)), the DCP (I_{DCP} (r)), and the SCA (I_{SCA} (r)) when comparing with the original 802.11 protocol versus transmitter-receiver distance *r*. The curves of the DCP and SCA intercept when r = *220*. When $r \geq 220$ (long range), the DCP (factor 1) plays a more important role than the SCA (factor 2) in terms of capacity improvements. When *r* increases, the advantage of the SCA diminishes since the size of *In Range* of a link expenses and gets closer to the

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size of *VCSRange*. This reduces the benefit obtained by releasing the protocol constraints that are induced by the virtual carrier-sensing mechanism. On the other hand, when *r* increases, the area of the exclusion region E_{DCP} decreases and thus links can be packed closer to each other. This reduces the interlink distances and makes factor 1 the dominant factor for the capacity improvements. When $r \le 220$ (short range), the area of the exclusion region increases when the transmitter-receiver distance r decreases, and thus, the advantage of factor 1 diminishes. Since In Range decreases with r, factor 2 overrides factor 1 by permitting closer link packing and become the prominent factor for capacity improvements.

The DCPwSCA integrates the benefits of the DCP (factor 1) and the SCA (factor 2) in long range and short range transmitter-receiver distance *r*. This significantly reduces the exclusion region $E_{DCPwSCA}$ and boosts capacities. Theoretically, **Fig. (9)** shows that the capacity can be boosted from 6.1 to 14.8 times of that of original 802.11 protocol when *r* is between 150 and 250 m.

V. SIMULATION RESULTS

It is assumed to set *VCSRange* and the *TxRange* to be 500 and 250 m. respectively. All data sources are saturated user datagram protocol traffic streams with a fixed packet size of 1450B. The original 802.11 protocol with RTS/CTS mechanism is used for comparisons, the capacity improvement will be reduced for the small packet size.

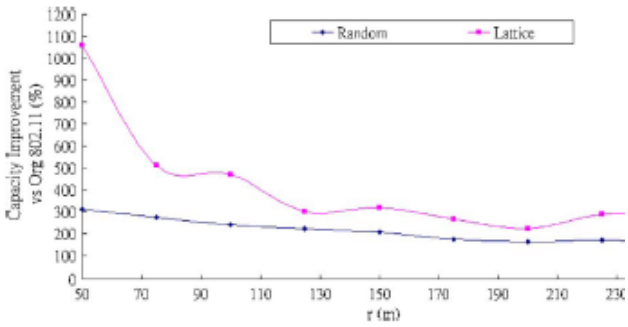

Fig. (10). Simulation results of capacity improvements of the DCPwSCA against the original 802.11 protocol versus the transmitter-receiver distance *r* in lattice topologies and random topologies with 80 single-hop links.

A. *Lattice Topologies*

Fig. (10) shows the capacity improvements obtained by the DCAwSCA in lattice topologies. Single-hop links with transmitter-receiver distance r are packed as many as possible in a *2000* × *2000* m square. The interlink distance is set to be *2.5* r*. When *r* = *50*, the DCPwSCA improves the network capacity of the original 802.11 protocol by *10.49* times. In the worst case, when *r* = *200*, the improvement is *221%*. On average, the capacities are multiplied by *428%*. The capacity improvement of lattice topology is not comparable with the theoretical results of **Fig. (9)** since they are based on different topology assumptions. **Fig. (9)** assumes a perfect topology that allows nodes to fully fill a given area without overlapping or waste of exclusion regions, whereas here, there are areas that are not covered by the exclusion regions of nodes in the lattice topologies.

B. *Random Topologies*

In each random network, *80* single-hop links with transmitter-receiver distance r are randomly placed inside a *3000* × *3000* m square. The entire topology of each link-length simulation is randomly regenerated. On average, the capacities are boosted by *215%*. The lowest improvements is *154%* when *r* = *200* and the highest is *306%* when *r* = *50*.

Simulation shows that the DCPwSCA can significantly multiply the network capacities in both lattice and random topologies.

VI.CONCLUSION

To characterize the capacity of wireless ad hoc networks, the capacity metrics can be classified into two groups: metrics based on a statistical approach, and metrics based on network scalability.

In the first group, capacity metrics incorporate aspect from the physical layer (e.g. modulation parameters, spectral efficiency etc.) and from the network layer (e.g. spatial reuse, number of hops etc.). Therefore, these metrics are suitable for network design and parameter optimization. Apart from it, some capacity metrics like Expected Forward Progress, Information Efficiency, Transmission Capacity and Aggregate Multi-hop Information Efficiency.

In the second group, the capacity metrics describe how network capacity behaves when the number of nodes in the network grows. The scaling laws are related to transport capacity and throughput capacity in terms of the protocol interference model and the physical interference model respectively. Therefore, even though the resulting scaling laws are rather pessimistic (per-node capacity vanishes as the size of the network increases), the results can be used for the design of more appropriate transmission schemes.

Apart from it, this paper has been an attempt to multiply network capacities of IEEE 802.11 ad hoc networks by two channels. The DCPwSCA integrates two analysis to boost network throughputs: 1) a link-directionality-based DCP and 2) an SCA.

For analysis 1, it splits the transmission and reception channels of a node so that transmissions in one channel do not interfere with the receptions in another non overlapping channel.

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For analysis 2, it releases the protocol constraints that are imposed by the virtual carrier-sensing mechanism. Links can decide their transmission processes based on the physical interference constraints instead of the receptions of RTS/CTS packets, as in the original 802.11 protocol. The performance improvement is achieved by analysis 1 and 2. It is demonstrated that analysis 1 outperforms analysis 2 in long interlink distances, whereas analysis 2 outweighs analysis 1 in short interlink distances.

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