Final Report on Capacity Survey

Group 15 LiuJing QinJiamei XuXin ChenXi

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Abstract- *Wireless network has been studied several years. As a basic characteristic, capacity draw a lot of attention of thousands of researchers and many significant improvement has been achieved under different assumption or model. This paper build a system model for wireless network, set up a standard for capacity. In the end of this paper, we illustrate some popular techniques and show how their contribution to capacity respectively.*

I. Introduction

In recent years there has been significant and increasing interest in wireless networks. A variety of new techniques and good result on capacity has been approached. All of these achievement is based on certain assumption or under certain circumstance. Thus, to compare, analysis them, we set up a system model for wireless network. As show in Figure1, there are four layers in all. Traffic Pattern describe who packets are transmitted. The common used by many researches are unicast and multicast. For Network model, there are two sub-categories. One is defined in terms of the transmission area, the other is grouped by how nodes distribution. The second layer view the wireless network from physical transmission point of view.

Traffic Pattern	Unicast Multicast Anycast Convergent cast
Network Model	Dense network Extended network Constant range network
	Arbitrary Model Random Model
Transmission Model	Physical Model Protocol Model Information Theoretical Model
Techniques	Mobile Directional Antenna MIMO Network Coding MPT&MPR Hybrid Network

Figure 1: System Model

The paper is organized as below. The first part(section II) set up the system model, giving definitions of all system patterns. The second part discuss several powerful methods to improve the capacity. The analysis is based on system model set up previously. In section III,we talk about unicast case while in section IV, we focus on multicast transmission model. We also introduce hybrid network, which combine pure ad hoc network and traditional cellular network in section V. In the end, we make a conclusion and talk about our future work.

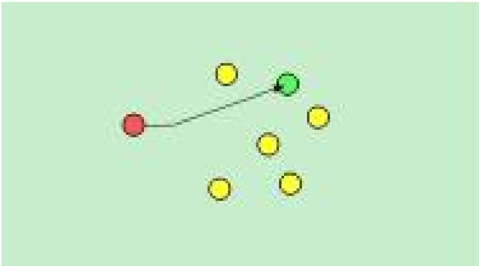

Figure 2: Unicast

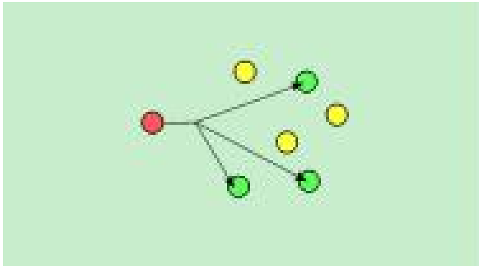

Figure 3: Multicast

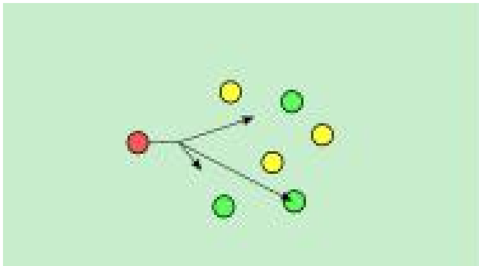

Figure 4: Anycast

II. System Model

Capacity Definition

The transport capacity of a specific network is defined as the maximum *bit·meters per second* the network can achieve in aggregate. The transport capacity of n nodes is the maximum of all achievable transport capacities networks with n nodes in a disk of area A C the difference is that in this latter case the locations of the n nodes are also allowed to be optimized, as are the choices of sourceCdestination pairs.

Thus, if a network is able to support a rate of λ_{ij} bits per second from each node i to each node j, then the transport capacity of the network is the supreme of $\sum_{i \neq j} \lambda_{ij} \mid X_i - X_j \mid$ over all such supportable rate vector $\{\lambda_{ij} : 1 \leq i, j \leq n\}$.

Notice only the distance between the original source and the final destination counts; extra distance traveled due to, say, non-straight line routing is not counted.

A. Traffic Pattern

There are four kinds of traffic patterns: unicast, multicast, anycast and convergent cast. To illustrate them clearly, look at the figures below. Unicast describe the one-to-one transmission. One node only transmit a packet to one relay or destination at one transmission period. Multicast is defined as the case of one-to-n transmission. That means one node can transmit to more than one nodes at the same transmission period. These two patterns are most frequently used.

Anycast is an addressing mode in which the same address is assigned to multiple hosts. Together, these hosts form an anycast group and each host is referred to as an anycast group member. Packets from a client destined to the group address are routed to the anycast group member closest to the client, where "closest" is in terms of the metrics used by the specific routing protocol.[1] An anycast forwarding scheme can substantially reduce the one-hop delay over traditional schemes, especially when nodes are densely deployed.

J.A. Cobb first presented Convergent multipath routing(also called convergent-cast)[2]. Convergent cast is a protocol for maintaining multiple paths to each destination in a network of processes. For each destination, each process in the network maintains a set of neighbors which are used as next-hops to reach the destination. This set is known as the successor set. Collectively, the successor sets from all processes in the network with respect to a given destination form a spanning, directed, and acyclic graph, whose only sink is the given destination.

The protocol has two interesting properties. First, the graph is maintained acyclic at all times, even though the successor set is dynamic. Second, the protocol tolerates all types of transient faults, even those which may not be detected.

Therefore, if the protocol is started from an arbitrary initial state, it will converge to a normal operating state in which a spanning, directed, and acyclic graph is obtained and subsequently maintained.

B. Network Model

We consider large scale networks. Typically there are three ways to increase the number of network nodes to infinity.

1. One is to fix the deployment region and then increase the node density to infinity. This is typically called the dense model. This model is widely studied, e.g., Gupta and Kumar studied the critical transmission range (CTR) [17] and the capacity for unicast [16] using this model.

2. Another way is to fix the node density to a given constant and increase the deployment region to infinity. This is typically called the extended model. Notice that to get a connected network with high probability, we also need to increase the transmission range of nodes. This model is also used by several papers to study the CTR or capacity, e.g., [18, 20].

3. The third way is to fix the transmission range of all nodes to some constant, then increase the node density (asymptotically same as the node degree when the transmission range is fixed) and the deployment area to increase the number of nodes in the network. We call this model the constant-range model. Assume that n nodes will be deployed. It has been proved in [19] that the minimum node degree for connectivity is $\Theta(logn)$. This implies that the area of the deployment region is at most $\Theta(\frac{n}{logn})$.

Because nodes transport packets to each other, distribution of the nodes are of great importance in the analysis and design of wireless network.

1.Consider a random network where n nodes are uniformly and independently distributed in a unit square. Each node has a random destination - a node - it wishes to send packets to. The destination for node X_i, $i \in \{1, ..., n\}$, is chosen as follows. A position is first picked uniformly from within the unit square, then the node nearest to it is chosen as node X_i's destination.

Order of The Throughput Capacity of Random Wireless Networks: The throughput capacity of random wireless networks is said to be of order $\Theta(f(n))$ bits per second if there exist deterministic positive constants c and c' such that

$$\lim_{n\to\infty} Prob(\lambda(n) = cf(n) \text{ is feasible }) = 1;$$

while

$$\lim_{n\to\infty} Prob(\lambda(n) = c'f(n) \text{ is feasible }) < 1.$$

2.For arbitrary network where n nodes are arbitrarily located in a disk of area A on the plane let Xi denote the location, as well as the identity, of a node. At each node Xi, there is originating traffic of rate ij which is destined for a remote node j. Each node can choose an arbitrary range or power level for any transmission.

We assume that each node can transmit at W bits per second over a common wireless channel shared by all nodes. It will be shown that it will not change the ensuring capacity results if the channel is broken up into several sub-channels of capacity $W_1, W_2, ..., W_M$ such that $W = W_1 + ... + W_M$.

C. Transmission Model

a. Protocol Model

Suppose all nodes employ a common transmission range r for all their transmissions. Node Xi can success- fully transmit to node $X_{R(i)}$ if

i) The distance between the transmitter and the receiver is no more than r, i.e.,$| X_i - X_{R(i)} |\leq r$.

ii) For every node $X_k, k \neq i$, transmitting at the same time, $| X_k - X_{R(i)} |\geq (1+\Delta)r$.

iii) The data rate between such successful transmitter-receiver pair is W bits/second. The quantity $\Delta > 0$, or more properly a circle of radius $(1+\Delta) \mid X_i - X_j \mid$ quantifies a guard zone required around the receiver to ensure that there is no destructive interference from neighboring nodes transmitting on the same m-th sub-channel at the same time.

There is also a variant of the Protocol Model: Suppose node X_i transmits over the m-th sub-channel to a node X_j at rate W_m bits/sec. Then this transmission is postulated to be successfully received by node X_j if

$$| X_k - X_j |\geq (1+\Delta) \mid X_k - X_l \mid$$

for every other node X_k simultaneously transmitting over the same m-th sub-channel, with X_l denoting intended the recipient of node X_k's transmission.

b. Physical Model

All nodes employ a common transmission power P for all their transmissions. Node X_i can successfully transmit to node $X_{R(i)}$ if

i) The signal to interference plus noise ratio(SINR) at the receiver is no less than a threshold β, i.e., assuming $X_k; K \in T(t)$ is the subset of nodes simultaneously transmitting at time t, then

$$\frac{\frac{P}{|X_i - X_{R(i)}|^\alpha}}{N + \sum_{k\in T(t), k\neq i} \frac{P}{|X_k - X_{R(i)}|^\alpha}} \geq \beta,$$

where N is the ambient noise power level. The signal power is assumed to decay with distance γ as $\frac{1}{\gamma^\alpha}$, with $\alpha > 2$.

ii) The data rate between every successful transmitter-receiver pair is W bits/second.

c. Theoretical Model

Signals are transmitted in physical media, so impairments including attenuation and fading are bound to interfere wireless network performance. A more practical model is Theoretical Model, it consider the physical layer interference but more complicate to analysis.

1.Attenuation

Suppose there are n nodes denoted by $i \in N := 1, 2, ..., n$. The distance between two nodes i, j is denoted as d_{ij}. Nodes in the network are assumed to be separated by a distance of at least $d_{min} > 0$, i.e., $d_{ij} \geq d_{min}$ for all $i \neq j$. Note that this implies that as n increases the network domain must keep growing at least linearly in the number of nodes.

We suppose that transmission happen in discrete time. At time instants $t = 1, 2, ...,$each node $i \in N$ transmits a signal $X_i(t)$.

After attenuation due to distance, the received signal $Y_j(t)$ at node j is

$$Y_j(t) = \sum_{i \neq j} \frac{Ge^{-\gamma d_{ij}}}{d_{ij}^{\delta}} X_i(t) + Z_j(t),$$

where $Z_j(t)$ is iid noise with Gaussian distribution of zero mean and variance σ^2. $G > 0$ is a constant gain. The parameter $\delta > 0$ is called the *path loss exponent*, while $\gamma \geq 0$ is called *absorption constant*. A positive γ generally prevails except for a vacuum environment.

Next, we define the Feasible rate vector with power constraint:
A rate vector $(R_{ij}, i, j \in N)$ is said to be feasible with total power constraint P_{total}, if there exists a sequence of $((R_{ij}, i, j \in N), T)$ codes such that $1/P \sum_{t=1}^{T} \sum_{i=1}^{n} X_i(t)^2 \leq P_{total}$, a.s., with $P_e^{(T)} \to 0$, as $T \to \infty$, the rate vector is said to be *feasible with individual power constraint P_{ind}*.

Definition of transport capacity: An n-node network's transport capacity is defined as

$$C_T(n) := sup_{(R_{ij}, i, j \in N) feasible} \sum_{ij} R_{ij} \times d_{ij},$$

where d_{ij} is the distance between nodes i and j.

2.Fading
In wireless communications, due to the physical environment, for example walls and trees, the electromagnetic waves travel to receivers along a multitude of paths. Along each path, the signal could encounter reflection, delay and path loss, which vary with time.

A common discrete model for a point-to-point fading channel is the tapped-delay baseband model, in which the received signal Y (t) is given by

$$Y(t) = \sum_{l=0}^{L-1} H_l(t) X(t-l), t = 1, 2, \cdots,$$

where L is the number of paths and $H_l(t)$ is the path gain for the l-th path. Network Model under large fading ($L = \infty$):
Consider a network consisting of n nodes in N := 1,2, . . . , n, located on the plane. The base-band model for the communications among them is described by the following equation:

$$\begin{aligned} Y_j(t) &= \sum_{i\ =j} \frac{Ge^{-\gamma d_{ij}}}{d_{ij}^{\delta}} \\ &\quad (\sum_{l=0}^{\infty} H_{ijl}(t) \cdot X_i(t - \tau_{ij} - l)) + \\ &\quad + Z_j(t), t \geq 1, j \in N. \end{aligned}$$

Network Model under small fading ($L < \infty$)
When there are no more than L paths for every channel, the baseband model for the communications in the network is described by the following equation:

$$\begin{aligned} Y_j(t) &= \sum_{i\ =j} \frac{Ge^{-\gamma d_{ij}}}{d_{ij}^{\delta}} \\ &\quad (\sum_{l=0}^{L-1} H_{ijl}(t) \cdot X_i(t - \tau_{ij} - l)) + \\ &\quad + Z_j(t), t \geq 1, j \in N. \end{aligned}$$

Let's summarize the first three layers in a picture. In the second part, we talk about eight important methods either as the benchmark of the process, or methods that still attracts people to investigate.

III. Unicast Techniques

A. Mobility

Since the capacity of wireless network was first introduced by Gupta and Kumar [35], there has been a tremendous interest in the

- Traffic Pattern:
  Unicast, Multicast, Anycast, Convergent cast
- Network Model:
  - Dense Model, Extended Model, C-range Model
  - Arbitrary Model, Random Model
- Transmission Model:
  Protocol Model, Physical Model, Infomation Theoretical Model

Figure 5: Summary of First Three Layers of System Model

study of the limit of the capacity in the wireless ad-hoc network. In [35], it was shown that in a random static network with n source nodes distributed independently and uniformly on a unit disk and each node, which is working as a source node has a randomly chosen destination node, can transmit at W bits-per-second provided that the interference is sufficiently small. In their report, they constructed two models and gave the results of the thoughput of per nodes under these model and corresponding distributions. The results are listed as follows: when nodes are arbitrary distributed in a region of area A in the protocol model, and the constraint on range is also arbitrary,the thoughput per node per area is $\Theta(W\sqrt{An})$ bit·meter/sec; when nodes are randomly distributed in a finite domain with a common transmission range r in the protocol model,the thoughput per node is $\Theta(\frac{W}{\sqrt{nlogn}})$ bit/sec; when nodes are arbitrary distributed in a region of area A in the physical model, and the transmission power is smaller than $\Theta((nA)^{\alpha/2})$,the thoughput per node per area is $\Theta(W\sqrt{An})$ bit·meter/sec; when nodes are randomly distributed in a unite square with a common common transmission power P in the physical model,the thoughput per node ranges from $\theta(\frac{W}{\sqrt{An}})$ bit/sec to $\theta(W/\sqrt{n})$ bit/sec.

However,the static network studied above in [35] has a drawback that the throughput of each node diminishes to zero when the node density grows,and this is a stationary network with all its nodes fixed without motivation.This suggests that only small ad hoc networks or networks supporting mainly nearest neighbor communications are feasible with current technology.

Since the capacity was introduced, many faculties have been trying to construct new models, protocols and technologies in order to enhance the above limit of the throughput.

In a network where nodes move randomly in a stable circular disk,the work [38] by Grossglauser and Tse shows that the average throughput per S-D pair can be kept constant even as the number of nodes per unit area increases when there are many nodes in the network as compared to having just a single S-D pair.They have shown that significant gains in the per-node capacity can be obtained by introducing the mobility of the nodes into the ad hoc network. The strategy for mobility introduced by Grossglauser and Tse is that each source node should split its packet stream to as many different nodes as possible,which is different from the relay-only nodes method where the relay nodes transmit the copy of the packets from the sourse. These nodes then serve as mobile relays and whenever they get close to the destination node, they hand the packets off to the destination. Since there are many relay nodes, the probability that at least one is close to the destination and then transmit the fraction of the packet to the destination is significant. During the transmission though relay nodes,each packet makes two hops, one from the source to its random relay node and the other one from the relay node to the destination. Since every packet has only one relay node, the total throughput is $\Theta(n)$. And it was also shown that the mobile network scheme they proposed can achieve a constant per-node capacity, which does not vanish as the number of nodes grows fairly large.

However,the strategy and analyze above in [38] doesn't take delay into consideration.And in fact it is usually delay sacrificed in order to obtain higher capacity.In the model studied in [38],the total throughput capacity of the nodes may be large,but when it comes to a single packet,the delay experienced through transmission may also be large.

In the paper of Swetha Narayanaswamy, Vikas Kawadia and P. R. Kumar [36],they mentioned that power control can enhance the traffic carrying capacity in some certain circumstances.Their protocol aims to operate all nodes at a common power level which is chosen to be the smallest power level at which the network is connected.In [36],a first cut simple solution for power control, the COMPOW protocol is proposed. In COMPOW, the goal of the optimization for each node is to choose a) a common power level b) set this power level to the lowest value which keeps the network connected, and c) keeps the energy consumption close to minimum.COMPOW works well if nodes are distributed homogeneously in space, but even a single outlying node could cause every node to use a high power level. So when the spatial distribution of nodes is inhomogeneous, it is obviously not optimal to use a common power level throughout the network. In [37],Vikas Kawadia and P. R. Kumar proposed the CLUSTERPOW architecture by allowing nodes to use a power level which depends on the destination of the packet, to increase network capacity by increasing spatial reuse.

B. Directional Antenna

Directional antenna technology offers a variety of potential benefits for wireless communication systems. In particular, it can improve spatial reuse of the system, which often results in substantially increased system capacity and wider coverage area. The utility of directional antennas has already been demonstrated in cellular networks via its deployment at base stations [31][32]; The deployment of directional antennas in MANET is more challenging than in cellular networks; first, a MANET node has no prior knowledge as to which other nodes it can communicate directly with, making it harder for directional antennas to beamform towards specific network nodes under dynamically changing network conditions. Second, while reducing interference, the directional communication may also reduce the number of neighbors recognized by each node, which can potentially affect the performance of MAC (Medium Access Control) protocols and destination discovery process performed by ad hoc routing protocols.

[33]presents a new carrier sensing mechanism called DVCS (Directional Virtual Carrier Sensing) for wireless communication using directional antennas. DVCS improved network capacity by a factor of 3 to 4 for a 100 node ad hoc network.

The performance evaluation in [34]suggests that using directional antennas may not be suitable when the network is dense or linear. However, the improvement in performance is encouraging for networks with sparse and random topologies.

C. Multi-Input Multi-Output (MIMO)

Multi-antenna systems (MIMO) are currently of great interest in all wireless communication systems due to their potential to combat fading, increase spectral efficiency, and potentially reduce interference. Compared to the one antenna case, MIMO systems enjoy more reliable communications (called diversity gain) and sometimes much higher data rate (called multiplexing gain). This is due to the fact that signals can be collected through different paths with different path gains; see[21]. The study of MIMO systems has been for some time now, e.g. [21][22] and the references therein.

Over the past decade, many different MIMO techniques have been proposed, which can be grouped into three broad categories: diversity-achieving, beam-steering, and spatial multiplexing. Diversity-achieving techniques increase reliability by combatting or exploiting channel variations. Beam-steering techniques increase received signal quality by focusing desired energy or attenuating undesired interference. Spatial multiplexing aggressively increases the data rate by transmitting independent data symbols across the antenna array.[23]

Furthermore, it is unclear which MIMO technologies yield the highest gains in large random networks. [24] For example, [25] based on a game-theoretic analysis shows that capacity is maximized for mutually interfering sources when each sends only one data stream, while [26] and [27]suggest capacity is improved through spatially multiplexing potentially multiple transmissions; however, [26] again focuses on asymptotics in the number of nodes and the results of [27]are obscured by the mobility/delay issue. Furthermore, [28] and [29]show that the reliability of MIMO is highly dependent on the SNR. A recent notable result in [26] gives a network spectral efficiency bound for MIMO ad hoc networks analyzing the throughput of a set of transmitterreceiver pairs. The implication is again that throughput decays with increasing network size unless a large degree of interfering channel information and coordination are available. The study also shows the optimality of beamforming without elaborate channel state information. Based on limited numerical work [29]indicates that many MIMO techniques perform similarly in networks as in point-to-point links. However, some specific counterexamples will be established here showing the presence of interference alters the relative gains of diversity techniques on network capacity.

For a Single-Input Single-Output (SISO) communication system in additive white Gaussian noise, the theoretical (narrowband) capacity that is obtainable C_s, was shown by Shannon to be

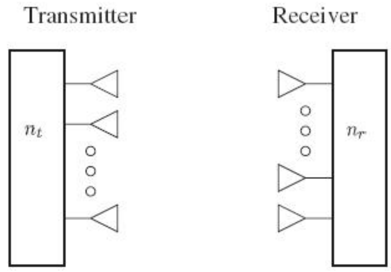

Figure 6: MIMO network

$$C_s = log_x(1 + E_s/N_0) = log_2(1 + SNR)[bps/Hz]$$

Where E_s is the symbol energy, N_0 is the noise energy in the receiver.

A typical setup is a MIMO system with nt transmit antennas and nr receive antennas. It is random network under physical model. If one denotes by h_ij the channel gain from the i-th transmit antenna, $1 \leq i \leq n_t$, to the j-th receive antenna, $1 \leq j \leq nr$, then assuming additive Gaussian noise the system can be described by the following equation.

$$Y = H_{nr \times n_t} X + Z$$

where $H_{nr \times nt}$ is a $n_r \times n_t$ matrix with entries h_{ij}, Z is Gaussian noise with power ^{2}, and X and Y are two vectors denoting the transmitted signal and received signal, respectively. In addition, the signal vector X is subject to a power constraint: $E \parallel X_i \parallel^2 \leq P_i$, for $1 \leq i \leq nt$. It can be shown that the maximum information rate is achieved by using Gaussian random code books, i.e., with X is a vector of Gaussian random variables; see e.g.,[21][22]. Let us denote the covariance matrix of X by K_x. If H is only known to the receiver, then the maximum rate achievable is

$$\max_{0 \leq K_x, K_{xii} \leq P_i} E[logdet(I + \frac{1}{\sigma^2} HK_2H^{\dagger})],$$

where $0 \leq K_x$ denotes that K_x is non-negative definite. However if H is known to both the transmitter and the receiver, the maximum rate is

$$E[_{\max_{0 \leq K_x, K_{xii} \leq P_i}} E[logdet(I + \frac{1}{\sigma^2} HK_xH^{\dagger})]$$

Note that now K_x is a function of H. Consider an n-node network, $N := X_1, X_2, , X_n$, on the plane. The (discrete time) communications are in an i.i.d flat fading environment. Specifically, the received signal at node j at time t is

$$Y_i(t) = \sum_{i\ =j} \frac{H_{ij}(t)}{d_{ij}^{\delta}} X_i(t) + X_j(t)$$

where $X_i(t)$ is the signal transmitted by node X_i at time t, d_{ij} is the distance between nodes X_i and X_j, and $Z_j(t), \forall j, t$ is i.i.d circular Gaussian noise with variance σ^2. $H_{ij}(t), t \geq 0$ is a stationary and ergodic stochastic process, with the marginal probability distribution symmetric with respect to the origin, and independent for each pair of nodes $(X_i, X_j\ )$. For simplicity we assume that $E \mid H_{ij}(t) \mid 2 = 1$ for all i, j, t. Furthermore, we suppose that each node X_i is subject to an individual power constraint P_i. The following is an upper bound on the transport capacity: If the channel state information (CSI) $H_{ij}(t), \forall i, j, t$ is known, then the transport capacity is upper bounded by

$$\frac{1}{\sigma^2} \sum_{i,k,j=1}^{n} \frac{\sqrt{P_i P_k} min(d_{ij}, d_{kj})}{d_{ij}^{\delta} d_{kj}^{\delta}}.$$

If instead the CSI is unknown, then the transport capacity is upper bounded by

$$\frac{1}{\sigma^2} \sum_{i,j=1}^{n} \frac{P_i d_{ij}}{d_{ij}^{2\delta}}.$$

Furthermore, a straightforward way to evaluate a physical layer technique under given per node service requirements is to determine the maximum allowable density of concurrent transmissions, or the optimal contention density, for which each node's requirements are still met. This leads naturally to the transmission capacity metric which is defined in [30] to be the maximum allowable spatial density of successful transmissions multiplied by their data rate given an outage constraint. For an outage constraint ϵ and a transmission data rate b in bits/Hz or per channel use, the transmission capacity is given by

$$C_\epsilon = b(1 - \epsilon)\lambda_\epsilon$$

for the optimal contention densityλ_ϵ. The transmission capacity is then the area spectral efficiency resulting from the optimal contention density.

D. MPT and MPR

The above works mainly studied one-to-one communication, that is there is only one packet from its source node to its destination node transmitting at a time slot. Then some wondered whether it may increase the throughput in a many-to-many communication pattern. Actually in wireless random access channels, a common channel is shared by many users. The conventional assumption on the reception capability of the common channel is that when two or more packets are transmitted simultaneously a collision occurs and consequently, the information is lost. To recover the information, the colliding packets have to be retransmitted involving undesired effects on the throughput and packet delay of the network. Many current signal processing techniques introduce multi-packet reception capability at physical layer by means of spatial, time, frequency or code diversity.

Ghez et al. [41, 42], and Tong et al. [48] present the first model of MPR in a framework for many-to-one communication.In this context, multiple nodes cooperate to transmit their packets simultaneously to the same node using directional antennas, multiuser detection (MUD), or multiple input multiple output (MIMO) techniques [43, 44, 45]. The receiver node utilizes MUD and successive interference cancelation (SIC) to decode multiple packets [46].

In short, under a many-to-many communicaiton paradigm, senders and receivers collaborate rather than compete with one another to access the channel and to relay information. Each transmitting node either relays a message to all close nodes or delivers a packet to one of the neighbor nodes if it is the destination. Using a many-to-many communication approach to design the communication protocols can substantially increase the capacity of an ad hoc network compared to the capacity attained under the one-to-one communication paradigm used to date. Many-to-many communication is a vision for multiple concurrent communication settings, i.e., a many-to-many framework where multi-packet transmissions (MPTs) and multi-packet receptions (MPRs) occur simultaneously. In this scheme, nodes access the available channel(s) and forward information across a MANET in such a way that concurrent transmissions become useful at destinations or relays. Assuming that the cell size limits the number of nodes in each cell, on average, making it feasible to decode the dominant interference using multiuser detection. Hence, sender-receiver pairs collaborate, rather than compete, and the adjacent transmitting nodes with strong interference to each other are no longer an impediment to scaling laws but rather an acceptable communication by all receiving nodes for detection and relaying purposes. MPT and MPR per node are enabling nodes to relay each other packets with the possibility of multi-copy forwarding to reduce delay and no capacity loss [48]. A consequence of such a strategy is an increase in the receiver complexity of all the nodes in the network.

And it's shown in [40] that by utilizing mobility, multiuser diversity(a node transmits a packet to all its nearest neighbors, and those relays deliver the packets to the destinations when each destination becomes a close neighbor of each relay), SIC, cognition(allowing a node to know where it is and who the nodes in the same cell are) and bandwidth expansion, the link's Shannon capacity and the per S-D throughput attain an upper-bound of $\Theta(n^{\frac{\alpha}{2}})$ and a lower-bound of $\Omega[f(n)]$, for n total nodes in the network, a path loss parameter $\alpha > 2$, and $1 \leq f(n) < n^{\frac{\alpha}{2}}$.

In [47], Zheng Wang and Hamid R. Sadjadpour focus on the cost incurred by approaches aimed at increasing the order capacity of a wireless ad hoc network subject to multiple unicast flows. They constructed a model which was similar to those made by Gupta and Kumar [35], except that each node is equipped with MPR capabilities, and the $\Theta(\frac{(R(n)^{1-2/\alpha})}{n^{1/\alpha}})$ bits per second constitutes a tight bound for the throughput capacity per node in random wireless ad hoc networks, where R(n) and α are the MPR receiver range and channel path loss parameter, respectively. When $R(n) = \Theta(\sqrt{\frac{logn}{n}})$, the throughput capacity is tight bounded by $\Theta(\frac{(logn)^{\frac{1}{2}-\frac{1}{\alpha}}}{\sqrt{n}})$.

IV. Multicast Techniques

A. Mobility

Keshavarz-Haddad and Riedi [13] studied the multicast capacity of large-scale random networks under a variety number of interference models: PrIM, fPrIM, and Gaussian channel model. They proposed some novel concepts: arena and some large separated cluster. Arena is introduced in [14]. They also present a novel constructive lower bound on multicast capacity by partitioning the deployment region using super-cells (with side length $\Omega(\log n)$, large cells (with side length $\Omega(\sqrt{\log n})$), and cells (with side length $\Omega(1)$) for three different purposes. The proofs on the capacity achievable by their routing and scheduling mechanisms are mainly based on the expected valuation, which could be far different from the result that needs to be true with high probability. We found that their results have discrepancies when $k > \frac{n}{\log n}$: Their results on total capacity $\Theta(W)$ cannot be achieved by broadcast when [6].

Furthermore, [13] studied the multicast capacity of large mobile wireless networks. They showed that similar to unicast case, mobility increases the capacity of wireless networks for multicast asymptotically. They proved that the multicast capacity is $\Theta(Wn/k)$; this implies that mobility can increase the multicast capacity by at least factor of $\Omega(\sqrt{n/k})$. This is in agreement with the previous results on unicast capacity and broadcast capacity of mobile networks [7], [15]. They also proved that $\Theta(Wn/k)$ is achievable using a mobility-based routing scheme. They employed a routing scheme similar to the scheme of [7]. However, the mobility gain decreases when increasing the ratio of the number terminals to overall size of the network. In the extreme case where multicast is equivalent to broadcast, the mobility gain reduces to a constant factor.

B.Directional Antenna

The capacity of ad hoc wireless networks is constrained by the interference between concurrent transmissions from neighboring nodes. Thus, directional antenna was introduced to ad hoc wireless networks to reduce the disadvantages. An omni-directional antenna (sometimes known as an isotropic antenna) radiates or receives energy equally well in all directions1. A directional antenna has certain preferred transmission and reception directions, that is, transmits/ receives more energy in one direction compared to the other.

Directional antennas have a number of advantages over omni-directional antennas in ad hoc networking. By focusing energy only in the intended direction, directional antennas can increase the potential for spatial reuse and can provide longer transmission and reception ranges for the same amount of power. Increased spatial reuse and longer range translates into higher ad hoc network capacity (more simultaneous transmissions and fewer hops), and longer range also provides improved connectivity. Translating this potential into reality requires support for antenna control at several layers of the protocol stack.

Much of the work on medium access has been done in the context of extending CSMA/CA (in particular IEEE 802.11) to work with directional antennas, including [49],[50],[51],[52]. A broad-based study of the performance potential of directional antennas in ad hoc networks appears in [53].

S Yi, Y Pei and S Kalyanaraman investigated the capacity of ad hoc wireless networks using directional antennas[54]. In this work, they considered arbitrary networks and random networks where nodes are assumed to be static. Their work is focused on discovering the lower bounds in capacity improvement that directional antennas can provide relative to the traditional omnidirectional antennas.

They obtained that for arbitrary networks, with the reduction of the transmission area and the reduced probability of two neighbors pointing to each other, the capacity of networks using directional antennas will be improved by a factor of $\frac{2\pi}{\sqrt{\alpha\beta}}$. Here α and β are the beamwidths of transmission and receiving directional antennas, respectively. If the beamwidths of transmission and receiving antennas are decreased asymptotically as fast as $\frac{1}{\sqrt{n}}$, the throughput capacity will keep constant with the increase of number of nodes in the network.

For random networks, due to the reduction of interfering neighbors, the throughput capacity with the use of directional antennas can achieve a gain as large as $\frac{4\pi^2}{\alpha\beta}$. The use of directional antennas can take advantage of decreasing both interference (local) and multi-hop relay burden (global) through the coordination of the transmission power and antenna directivity.

In[55], the authors presented the first complete system solution for utilizing directional antennas in ad hoc networks (UDAAN). The solution provided a significant improvement in network capacity. They designed an experiment to measure the quantitative gains of using directional antennas over existing omnidirectional ad hoc networks. The experiment considered multicast situation.

C. MIMO

Chen-Nee Chuah et al.[69]consider a single-user, point-to-point communication channel with n transmitting and n receiving antenna elements, denoted as an n,n-MEA system. They assume that the transmitted signal occupies a bandwidth W, over which the channel frequency response is essentially constant. For this assumption to be valid, must be much smaller than the channel coherence bandwidth, which is approximately the reciprocal of the channel delay spread.Since the maximum delay spread of our channels is about 25 ns, we require that W be much less than 40 MHz. Assuming zero excess bandwidth, this requires a symbol rate much less than 40 Mbaud. For the remaining analysis and discussions, they assume that the channel is linear and time-invariant and use the following discrete-time equivalent model:

$$Y = HX + Z$$

$X = [x_1, x_2, \cdots, x_T]^T$ is an n $\times$1 vector whose jth component represents the signal transmitted by the jth antenna. Similarly, the received signal and received noise are represented by n $\times$ vectors, and Y,Z, respectively, where y_i and z_i represent the signal and noise received at the ith antenna. The complex path gain between transmitter j and receiver i is represented by$H_{ij} : i, j = 1, 2 \cdots n$.

A. Ozgur etal.[65]Using visual MIMO for long-range communication to achieve spatial multiplexing. To achieve linear scaling, one must be able to perform many simultaneous long-range communications. A physical-layer technique which achieves this is MIMO (multi-input multi-output): the use of multiple transmit and receive antennas to multiplex several streams of data and transmit them simultaneously. MIMO was originally developed in the point-to-point setting, where the transmit antennas are co-located at a single transmit node, each transmitting one data stream,and the receive antennas are co-located at a single receive node, jointly processing the vector of received observations at the antennas. A natural approach to apply this concept to the network setting is to have both source nodes and destination nodes cooperate in clusters to form distributed transmit and receive antenna arrays respectively.see Figure 2. In this way, mutually interfering signals can be turned into useful ones that can be jointly decoded at the receive cluster and spatial multiplexing gain can be realized.

D. Network Coding

Network coding was introduced by Ahlswede et al. in their seminal paper [56], and has since received a lot of attention.

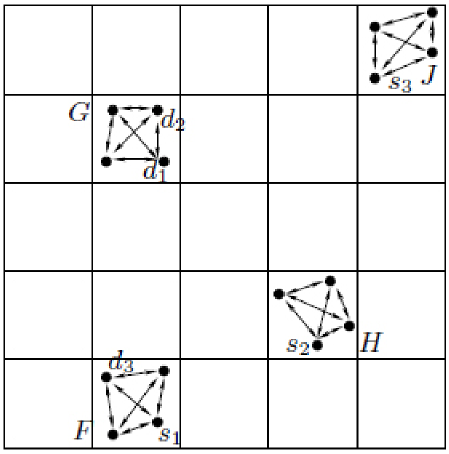

Figure 7: The time division in a hierarchical scheme as well as the salient features of the three phases are illustrated.

[56]showed that for multicast case, the information rate to each terminal is the minimum of the individual max-flow bounds over all source-terminal pairs under consideration and that in general we need to code over the links in the network to achieve this capacity. Li et al. [57] showed that linear network coding is sufficient for achieving the capacity in multicast. Subsequent work by Koetter and Mdard [58] and Jaggi et al. [59] presented constructions of linear multicast network codes. A randomized construction of multicast codes was presented by Ho et al. [60] and Chou et al. [61] demonstrated a practical scheme for performing randomized network coding. It is important to clearly differentiate between routing and network coding. We say that a network employs routing when each node in the network performs only a replicate and forward function. Thus, each node can create multiple copies of a received packet and forward it on different lines. Network coding, on the other hand, refers to the situation when each node has the ability to perform operations such as linear combinations on the received data and then send the result on different lines. So, routing is a special case of network coding. The usefulness of network

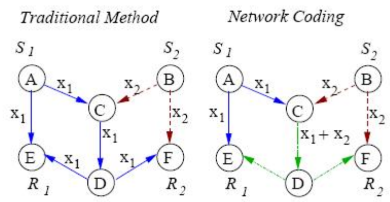

Figure 8: Butterfly Network

coding can be understood by considering a simple topology shown in figure of Butterfly Network from [56]. S1 and S2 multicast to both R1 and R2. All links have capacity 1. With network coding (by xoring the data on link CD), the achievable rates are 2 for each source, the same as if every destination were using the network for its sole use. Without network coding, the achievable rates are less.

A. Ramamoorthy et al studied the maximum flow possible between a single-source and multiple terminals in a weighted random geometric graph (modeling an ad-hoc wireless network) using network coding[62]. For the weighted random geometric graph model where two nodes are connected if they are within a certain distance of each other we show that with high probability the network coding capacity is greater than or equal to the expected number of nearest neighbors of the node with the least coverage area.

Network coding may offer throughput benefits not only for multicast, but also for other traffic patterns, such as unicast. We assume that source S1 transmits to destination R2 and S2 to R1 in the Butterfly Figure. With network coding we can send rate 1 to each receiver, while without, we can only send rate 1/2 to each receiver.

E. MPT and MPR

We denote by multipacket reception (MPR) [63] the ability of a receiver node to decode correctly multiple packets transmitted concurrently from different nodes, and by multi-packet transmission (MPT) the ability of a transmitter node to transmit concurrently multiple packets to different nodes. In practice, MPR and MPT can be achieved with a variety of techniques. For example, MPR can be implemented by allowing a node to decode multiple concurrent packets using multiuser detection (MUD); MPR or MPT capabilities can be implemented utilizing directional antennas [64] or multiple input multiple output (MIMO) techniques.

Wang et al.[66]assume a random wireless ad hoc network with n nodes distributed uniformly in a network of unit square area. Their capacity analysis is based on the protocol model for dense networks introduced by Gupta and Kumar [3].They present capacity scaling laws for random wireless ad hoc networks under (n, m, k)-cast formulation, where n, m, and k denote the number of nodes in the network, the number of destinations for each communication group, and the actual number of communication group members that receive information (i. e., k $\leq$ m $\leq$ n), respectively and when nodes are endowed with multi-packet transmission (MPT) or multi-packet reception (MPR) capabilities. We show that $\Theta(T(n)\sqrt{m}/k)$, $\Theta(1/k)$, and $\Theta(T^2(n))$bits per second constitute a tight bound for the throughput capacity of random wireless ad hoc networks under the protocol model when $m = O(T^{-2}(n))$, $\Omega(k) = T^{-2}(n) = O(m)$, and $k = \Omega(T^{-2}(n))$, respectively. This result applies to both MPR and MPT, where T(n) denotes the transceiver range, which depends on the complexity of the nodes. For the minimum transceiver range of $\Theta(\sqrt{\log n/n})$ to guarantee network connectivity, a gain of $\Theta(\log n)$ for (n, m, k)-casting is attained with either MPT or MPR compared to the capacity attained when transmitters and receivers can encode and decode at most one transmission at a time (i.e., point-to-point communication).

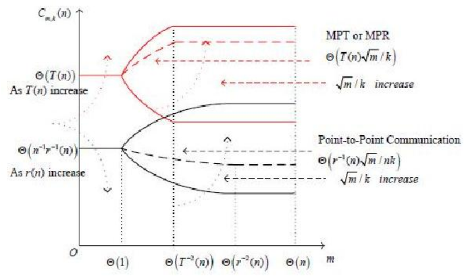

Figure 9: Order throughput capacity of (n, m, k)-cast with MPT or MPR and point-to-point communication

From the analysis from Wang et al.[66] , it is clear that MPT and MPR are two cooperative techniques that are equivalent in terms of capacity and delay scaling laws. MPT concentrates on increasing the encoding complexity at the transmitter, while MPR requires more decoding compexity at the receiver side. The fact that MPR and MPT are equivalent to each other in terms of capacity and delay scaling laws is important, because MPT may be a more practical approach to embracing interference than implementing MPR (e.g., by means of directional antennas or beam forming).

Wang et al.[66],J.J. et al.[68]study the contribution of network coding (NC) in improving the multicast capacity of random wireless ad hoc networks when nodes are endowed with multipacket transmission (MPT) and multi-packet reception (MPR) capabilities. We show that a per session throughput capacity of $\Theta(nT^3(n))$ where n is the total number of nodes and T(n) is the communication range, can be achieved as a tight bound when each session contains a constant number of sinks. Surprisingly, an identical order capacity can be achieved when nodes have only MPR and MPT capabilities. This result proves that NC does not contribute to the order capacity of multicast traffic in wireless ad hoc networks when MPR and MPT are used in the network. The result is in sharp contrast to the general belief (conjecture) that NC improves the order capacity of multicast. Furthermore, if the communication range is selected to guarantee the connectivity in the network, i.e., $T(n) \geq \Theta(\sqrt{\log n/n})$ then the combination of MPR and MPT achieves a throughput capacity of $\Theta(\frac{\log^{\frac{3}{2}} n}{\sqrt{n}})$which provides an order capacity gain of $\Theta(\log^2 n)$compared to the point-to-point multicast capacity with the same number of destinations.

V. Hybrid Network

In a wireless cellular network, a node communicates with its destination node by first connecting to the nearest base station or access point. And in an ad hoc network, a collection of nodes communicate with each other without the aid of any fixed base station. Ad hoc network is suitable for the situations when there is no fixed infrastructure, but if the distance between a source node and a destination node, data needs to be routed to the destination in a multi-hop fashion, which also causes great delay in time.

In a study[70], a hybrid network model is set up to improve network connectivity. The model is composed of a sparse network of Infrastructure (base stations) and an ad hoc network. We assume that the base stations are connected by a high-bandwidth wired network, and they act as relays for wireless nodes in an ad hoc network. The network presents a tradeoff between traditional cellular networks and pure ad hoc networks. Figure 4 is a pictorial representation of a hybrid network.

Based on the model, B. Liu , Z. Liu and

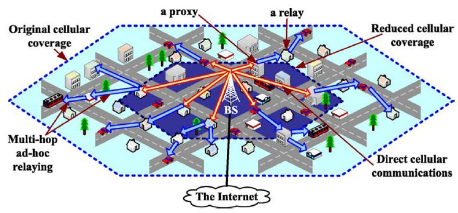

Figure 10: A pictorial representation of a hybrid network

D. Towsley study on the capacity of a hybrid network of m base stations and n nodes, each capable of transmitting at W bits/sec over the wireless channel,In study[71]. The authors find the maximum throughput capacities and the conditions to achieve them. The result is that the maximum throughput capacities are achieved when $W1/W \rightarrow 0$ or $W1/W \rightarrow 1$, where W1 is the channel bandwidth assigned to carry ad hoc mode transmissions.

There are two modes of data transmitting in the model, ad hoc mode and base station mode. We consider two routing strategies. In the first strategy, a node sends data in base station mode if the destination is outside of the cell where the source is located. Otherwise, data is transmitted in ad hoc mode. In the second strategy, a node chooses to use ad hoc mode or base station mode according to some probability.

In order to compare the capacity of hybrid networks and pure ad hoc networks, capacity gain factor is defined. The capacity gain factor g(n,m) of a hybrid network of n nodes and m base stations is the ratio of the maximum throughput capacity of the hybrid network to the throughput capacity of an ad hoc network of n nodes.

It is showed that for both strategies, there is a threshold for the scaling of the number of the base station (m) in term of the number of nodes(n). If m grows asymptotically slower than $\sqrt{n}$, the effect of adding base stations on capacity is insignificant, compared to the capacity performance of pure ad hoc networks. However, if m grows faster than $\sqrt{n}$, there is an effective improvement on capability over pure ad hoc networks. In this case, the maximum throughput capacity scales linearly with the number of base stations.This result is also achieved in[75]

Another research[72] shows that if all nodes adopt a common power level, then each node can be provided a throughput of at most $\theta(\frac{1}{logn})$ to randomly chosen destinations. And even under weak conditions, we can improve per node throughput significantly with hybrid networks.In[74],it is shown that a hybrid network with $n$wireless nodes and n^daccess points, interconnected by wires, can achieve throughput gains only when $0.5 < d < 1$.

We notice that an important assumption in the works above on hybrid networks is that all nodes choose a common power level. However, in[73], A. Agarwal and P. R. Kumar illustrate that by allowing nodes to perform power control and properly choosing μ, it is further possible to provide a throughput of $\theta(1)$ to any fraction $f, 0 < f < 1$,of nodes. For hybrid networks, the results underline the importance of building power control 2 into the protocol stack.

In[76], the authors analyzed capacity scaling laws of two routing protocols using BSs and compare them with those of the two conventional schemes MH(multi-hop) and HC(hierarchical cooperation) in both dense and extended networks. It was shown that the achievable schemes are order-optimal for all the operating regimes.

In[77],the authors derive asymptotic upper bounds and lower bounds on multicast capacity of the hybrid wireless networks. The total multicast capacity is $O(\frac{\sqrt{n}}{\sqrt{logn}} \cdot \frac{\sqrt{m}}{k} \cdot W)$when $k = O(\frac{n}{logn})$, $k = O(m)$, $\frac{k}{\sqrt{m}} \to \infty$ and $m = o(\frac{a^2}{r^2})$; the total multicast capacity is$\Theta(\frac{\sqrt{n}}{\sqrt{logn}} \cdot \frac{W}{\sqrt{k}})$when $k = \Omega(\frac{n}{logn})$, $k = O(m)$, and $\frac{m}{k} \to 0$.

In a recent research[78], the capacity of the network is formally defined as the maximum possible downlink throughput under the constraint of max-min fairness. The researchers evaluate the impact of the conflicting factors–improved spatial reuse and multihop forwarding–on the overall capacity of the hybrid network. This work proves that with careful parametric choices, the capacity of the hexagonal hybrid network can exceed that of the corresponding pure cellular network by as much as 70%.

VI. Conclusion and Future Works

In the paper, we build a system model including four layers: Traffic Pattern, Network Model, Transmission Model and various approaches to improve the capacity of wireless network. Based on this model, we analyze and summarize different kinds of algorithms or strategies which can improve the capacity of wireless network. We introduce 8 methods in all. Certain less important methods,such as power control has been ignored, readers can look at our reference ppt for some information. To summarize, mobility increase the capacity is the basic idea, while it is at the cost of unacceptable delay. Directional antenna and coding are techniques found long long ago but helpful is modern wireless networks. MIMO deal with multiple transmission while MPT,MPR focus on multi-packets. In the end, the hybrid take advantages of both ad hoc network and infrastructures. We don't consider the coverage, connectivity and packet delay-one of the most important concern in wireless transmission. A not too short comments can be found in both previous report 1 and 2 if necessary.

Since we have not add too much latest approaches in famous conferences, some new ideas may be added to this survey as soon as possible. And thanks for the help of Professor Wang.

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Group Members

Liu Jing(leader)
Done: Search papers,Write part of the report,Organize the final report.
I'd like to give thanks to my great group members. How great when we are together!

Qin Jia Mei
Done: Search papers,Write part of the report
Leader comments: A fortitudinous girl,continue to do presentation even after got hurt

Xu Xin
Done: Search papers,Write part of the report
Leader comments: A careful girl,often calm when coming into trouble

Chen Xi
Done: Search papers,Write part of the report
Leader comments: A diligent girl, give us a lot of ideas

Figure 11: Leader:Liu Jing

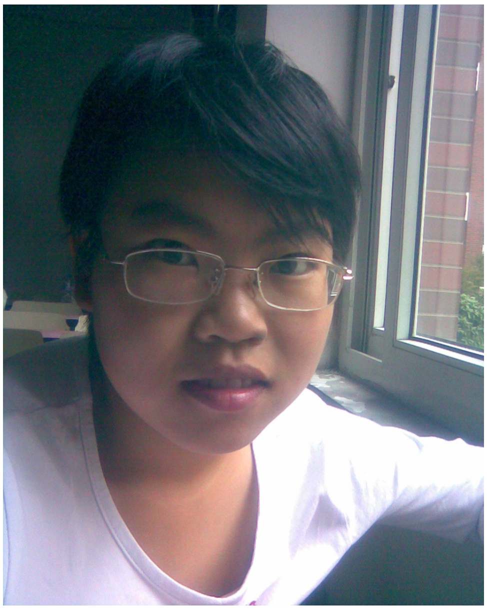

Figure 12: Qin Jiamei

Figure 13: Xu Xin

Figure 14: Chen Xi