On Collision-Tolerant Transmission with Directional Antennas

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***Abstract*—The application of directional antennas in wireless networks brings numerous benefits, such as increased spatial reuse and mitigated interferences. Most MAC protocols with directional antennas are based on the RTS/CTS mechanism which works well in wireless networks using omni-directional antennas. However, RTS/CTS frames cannot mitigate the interfering nodes completely. Besides, they also contribute a lot to the performance overhead. This paper studies the problem from a new perspective. We analyze the transmission success probability under directional transmission and directional reception when the antenna beamwidth is quite narrow. Motivated by the analytical results, we design a lightweight MAC protocol without RTS/CTS frames. The preliminary results demonstrate that this new protocol performs better than MAC protocols based on the RTS/CTS mechanism. The results also show that a collision-tolerant transmission is feasible under the narrow beam configuration.**

I. INTRODUCTION

The application of *directional* antennas to wireless ad hoc networks has received enormous interest in recent years. Directional antennas can greatly improve network performance by increasing network connectivity, expanding transmission range, enhancing spatial reuse and reducing interference. Recent works such as [1]–[10] focus on designing new MAC layer protocols to improve network performance.

Most of these MAC schemes with directional antennas are based on a four-way handshaking technique, known as request-to-send/clear-to-send (RTS/CTS). The RTS/CTS mechanism has been proposed to resolve the hidden terminal problem in wireless networks using *omni-directional* antennas which can broadcast RTS/CTS frames to inform neighboring nodes of the oncoming transmission. However, the use of RTS/CTS does not eliminate hidden terminals completely [11]. Furthermore, compared with omni-directional antennas, directional antennas have different transmission characteristics, such as radiating or receiving signals more effectively in one direction. Therefore, it is questionable whether the design of MAC protocols with directional antennas should be based on the RTS/CTS mechanism.

In a recent study [5], Choudhury et al. find that using directional antennas causes new interference such as new hidden terminals and deafness, which cannot be solved by using the typical RTS/CTS mechanism. Although Korakis et al. [3] propose a Circular-DMAC scheme to combat the new hidden terminal and deafness problems, transmitting multiple RTS/CTS frames for a single data transmission severely degrades the performance. Other schemes, such as Tone-based DMAC [7] and BT-DMAC [12] can alleviate the impacts of the hidden terminal and deafness problems by sending tones over another channel or over the data channel after data transmission. However, these bulky and complicated schemes also bring additional cost and performance penalty.

How to use directional antennas in wireless networks more effectively? We address this problem from another viewpoint. As we know that when the beamwidth of a directional antenna is lessened (a narrower beamwidth), the interference caused by the antenna will also be reduced. When the beamwidth is less than a certain degree and the node density meets a particular condition, collisions may happen with a very low probability. At this time, is the RTS/CTS mechanism still necessary? To the best of our knowledge, there is no study that analyzes the connection between the beamwidth of directional antennas and interference, especially for narrow-beam antennas. It is the purpose of this work to study the performance of ad hoc networks using narrow-beam antennas. In particular, we are interested in the following questions.

- How does the success transmission probability degrade with the increased beamwidth of directional antennas? What is the impact of the node density on the success transmission probability?
- How effective is the RTS/CTS mechanism in wireless networks using directional antennas? If RTS/CTS is turned off, will the network throughput have a noticeable degradation?

In the next section, we briefly survey the related works in the literature. Section III describes the models used in this paper and analyzes the success transmission probability for directional transmission and directional reception. In Section IV, we present a lightweight MAC protocol without the RTS/CTS mechanism and compare its performance with a representative MAC protocol using the RTS/CTS mechanism. Finally, our paper is concluded in Section V.

II. RELATED WORK

Many studies [1]–[10] focus on designing new MAC protocols with directional antennas. Most of them are based on the IEEE 802.11 MAC [13], which uses RTS/CTS to reduce interference in ad hoc networks. Although the RTS/CTS mechanism works well in wireless networks equipped with omni-directional antennas, it cannot mitigate interference completely [11]. Besides, using RTS/CTS in wireless networks with directional antennas is not so effective as we expected. For example, [5] shows that RTS/CTS cannot completely mitigate new interfering nodes caused by directional antennas.

To address the new hidden terminal and deafness problems, many researchers propose more complex schemes, such as Circular-DMAC [3], Tone-based DMAC [7] and BT-DMAC [12]. Although they can mitigate the impacts of hidden terminals and deafness, they also bring additional cost on network performance. For example, Circular-DMAC needs a sender to transmit multiple RTS frames before one data transmission, which greatly degrades the network performance. Tone-based DMAC and BT-DMAC also need to send busy tone signals with different frequencies to reduce interference.

Other studies concentrate on capacity analysis and performance evaluation on wireless ad hoc networks using directional antennas [14]–[17]. Yi et al. [15] show that using directional antenna in arbitrary networks achieves a capacity gain of $2\pi/\sqrt{\alpha\beta}$ when both transmission and reception are directional. Here, α and β are transmitter and receiver antenna beamwidths, respectively. Under random networks, the throughput improvement factor is $4\pi^2/(\alpha\beta)$ for directional transmission directional reception. Spyropoulos and Raghavendra [14] study the asymptotic bounds on the amount of capacity gains that directional antennas can acquire. Wang and J. J. Garcia-Luna-Aceves [16] model and analyze multiple directional transmission and reception modes coupled with omni-directional or directional receptions. Carvalho and J. J. Garcia-Luna-Aceves [17] propose a realistic analytical model which considers the binary exponential back-off operation of IEEE 802.11.

However, there is no work that studies the connections between the beamwidth of directional antennas and interferences, especially for narrow-beam antennas. We try to find the relationship between the beamwidth of directional antennas, the density of nodes and the interference.

III. ANALYTICAL MODELS

In this section, we analyze the successful transmission probability with directional antennas. The successful transmission probability is related to transmission/reception mode of directional antennas. Besides, interference is also a major reason affecting the transmission probability. First, we present the antenna model in Section III-A. Section III-B discusses the interference range for directional transmission. Finally, we analyze the successful transmission probability under the directional transmission and directional reception mode.

A. Antenna Model

In this paper, we consider a directional antenna model that is typically used in previous works (e.g., [1]–[3], [9], [10], [15]). Sidelobes and backlobes are ignored in this model. The reasons why we simplify the model are summarized as follows. First, even in a more realistic model, the sidelobes are so small that they can be ignored. For example, the main gain is more than 100 times of the gain of sidelobes when the main beamwidth is less than 40 ° in the cone-sphere model [18]. Secondly, a *smart antenna* (i.e., an intelligent directional antenna) often have null capability that can almost eliminate the sidelobes and backlobes. Besides, the interference region of an antenna is determined by its main lobe and simplifying the antenna pattern will not lead to a fundamental change on the analytical results [15].

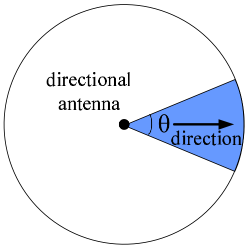


Fig. 1. The Antenna Model

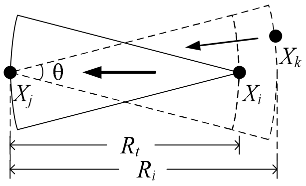


Fig. 2. The Interference Model

Our proposed model assumes that a directional antenna gain G^d is within a specific angle θ, where θ is the beamwidth of the antenna. The gain outside the beamwidth is assumed to be zero. At any time, the antenna beam can only be pointed to a certain direction, as shown in Fig. 1, in which the antenna is pointing to the right. Thus, the probability that the beam is switched to cover each direction is $\theta/2\pi$. The antenna gain pattern is given by :

$$g(\theta) = \begin{cases} G^d & \text{if angle within } \theta \\ 0 & \text{otherwise} \end{cases}$$

B. Interference Range

In this subsection, we investigate the interference range of directional antennas and the relationship between the transmission range and the interference range. When a signal is propagated from the transmitter to the receiver, whether it is correctly accepted by the receiver is mainly determined by the receiving power of the signal at the receiver end. In open space, if the transmitting power is fixed, the receiving power is mostly decided by the path loss along the distance between the transmitter and the receiver. Under this condition, multi-path and shadowing effects can be ignored since they are so trivial compared with the large path loss. Therefore, in this paper, we assume that the signal propagation follows the *two-way ground* model which is typically used in open space.

According to [19], under the assumption of the two-way ground model, the receiving power of a signal at the receiver can be calculated by the following equation.

$$P_r(d) = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \tag{1}$$

where $P_r(d)$ is the receiving power at the receiver which is far from the transmitter with the distance d, P_t is the transmitter power, G_t and G_r are the transmitter antenna gain and the receiver antenna gain, respectively, and h_t and h_r are the antenna height of the transmitter and the antenna height of the receiver, respectively.

Considering a large-scale wireless ad hoc network with n static nodes. All nodes are Poisson distributed with a density ρ over the 2-D plan. The probability $p(i,S)$ of finding i nodes in an area of S is given by:

$$p(i,S) = \frac{(\rho S)^i}{i!} e^{-\rho S} \tag{2}$$

We also assume that every node has the same setting (e.g., identical antenna, and identical transmitting power). In the scenario shown in Fig. 2, suppose that node X_i transmits to node X_j over a channel. The receiver X_j locates exactly within the transmitting range R_t of the transmitter X_i. The successful reception of the signal is mainly decided by the *signal-to-interference-plus-noise ratio* (SINR), which is often required to be greater than a threshold. When their transmission is on-going, an interfering node X_k at a distance of R_i away from the receiver starts the transmission toward the receiver at the same time. So, it will have an interfering signal with the strength P_i at the receiver X_j. Since the thermal noise is negligible compared with interference signals, similar to [11], we do not count it in our model as well. Thus, we have $SINR = \frac{P_r}{P_i} = \frac{R_i^4}{R_t^4} \geq \sigma$, where σ is the SINR threshold. In practice, σ is usually set to 10. So, we get the interference range $R_i = \sqrt[4]{\sigma} R_t$.

C. Analysis of Directional Transmission and Directional Reception (DTDR)

A directional antenna has two modes: an omni-directional mode with a gain G^o and a directional mode with a gain G^d. Since antennas in the directional mode can radiate or receive electromagnetic waves more effectively in some directions than in others, generally, the directional gain G^d is greater than the omni-directional gain G^o. The transmitter or the receiver equipped with a directional antenna can choose any one of the two modes to transmit or receive frames. Therefore, there are four combinations for the transmission and reception modes of directional antennas: 1) Omni-directional Transmission and Omni-directional Reception (OTOR); 2) Directional Transmission and Omni-directional Reception (DTOR); 3) Omni-directional Transmission and Directional Reception (OTDR); 4) Directional Transmission and Directional Reception (DTDR).

According to Eq. (1), the larger the antenna gains at both the transmitter and the receiver have, the higher the receiving power strength the receiver has. Furthermore, the transmission range between the transmitter and the receiver will be extended if the antenna gains of them are increased. Thus, when both the receiver and the transmitter use the directional mode (with the directional gain G^d), the communication range between them is maximized. On the other hand, the receiver is only susceptible to the interfering signals from its receiving direction when it is using the directional mode. So, DTDR also has the smallest interference area compared with the other three modes. Therefore, directional transmission and directional reception is a preferred method to utilize directional antennas. In this paper we only discuss the transmission under the DTDR mode.

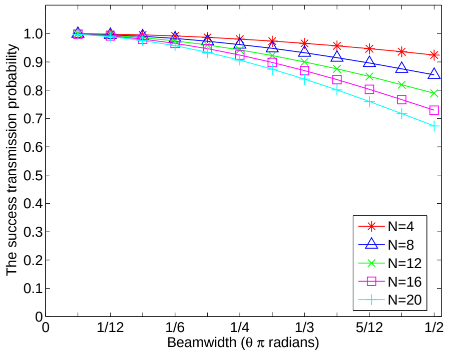


Fig. 3. The probability of a successful transmission and the beamwidth

Let us consider the scenario shown in Fig. 2. When node X_i begins to transmit with node X_j, this transmission is successfully completed by node X_j if no node within the sector region covered by X_j's antenna beam transmits toward X_j. First, we need to calculate the probability that no node can interfere with node X_j. Since the placement of nodes follows the 2-D Poisson distribution with the density ρ, there are $\rho \pi R_i^2 \cdot \frac{\theta}{2\pi}$ nodes within the sector region covered by X_j's antenna beam. The area of this region is denoted by S. Among these nodes, the interfering node X_k can cause interference with node X_j only when it has a frame to send and its antenna beam is pointed to node X_j. We assume that a node begins to transmit with a probability p. Then, the probability that node X_k can interfere with node X_j is $p \cdot \frac{\theta}{2\pi}$. Therefore, the probability P that no nodes within region S can cause collisions with node X_j is given by:

$$\begin{aligned} P &= \sum_{i=0}^{\infty} (1 - p\frac{\theta}{2\pi})^i \cdot \frac{(\rho S)^i}{i!} e^{-\rho S} \\ &= e^{-p\frac{\theta}{2\pi}\rho S} = e^{-p(\frac{\theta}{2\pi})^2 \rho \pi R_i^2} \end{aligned} \tag{3}$$

To simplify the calculation, we use $N = \rho \pi R_t^2$, which denotes the average number of nodes within a node's transmission range. Since $R_i = \sqrt[4]{\sigma} R_t$, we have $\rho \pi R_i^2 = \sqrt{\sigma} N$. Replacing the corresponding part in Eq. (3), we have:

$$P = e^{-p(\frac{\theta}{2\pi})^2 \sqrt{\sigma} N} \tag{4}$$

When $p = 0.1$, and $\sigma = 10$, which is in common use [11], we set different N, $N = 4, 8, 12, 16, 20$ respectively and then we get the results in Fig. 3. Fig. 3 shows that the successful transmission probability is kept high when the beamwidth is narrow. For example, when the beamwidth is less than $\frac{\pi}{6}$, the success probability is always above 95%. One possible reason is that using directional mode at the receiver end can greatly reduce the interfering probability.

Results under a narrow beamwidth ($\theta \leq \frac{\pi}{12}$) are also tabulated in Table I. It is shown that the transmission under DTDR is less vulnerable to interfering nodes when the beamwidth is narrow.

TABLE I
THE PROBABILITY OF A SUCCESSFUL TRANSMISSION UNDER THE VERY NARROW BEAM θ

	$\theta = \frac{\pi}{48}$	$\theta = \frac{\pi}{36}$	$\theta = \frac{\pi}{24}$	$\theta = \frac{\pi}{12}$
$N = 4$	0.9999	0.9998	0.9995	0.9978
$N = 8$	0.9997	0.9995	0.9989	0.9956
$N = 12$	0.9996	0.9993	0.9984	0.9934
$N = 16$	0.9995	0.999	0.9978	0.9913
$N = 20$	0.9993	0.9988	0.9973	0.9891

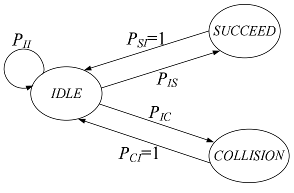


Fig. 4. The Markov chain model for a node

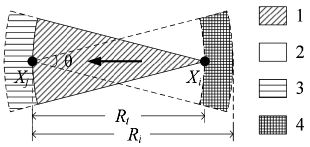


Fig. 5. The interference region for DTDR

The analytical results under DTDR show that the successful transmission probability is quite high when the beamwidth is lessened enough. For example, when $\theta \leq \frac{\pi}{12}$ (i.e., 15°), the success probability is always above 98%. Since a beamwidth of 15° is a feasible angle for most directional antennas, is a collision-tolerated transmission possible under this condition?

IV. LIGHTWEIGHT MAC PROTOCOL

We propose a lightweight MAC scheme denoted as Basic Directional Transmission and Directional Reception (BAS-DTDR), which turns off RTS/CTS. It has a rival termed RTC/CTS Directional Transmission and Directional Reception (RTS-DTDR). Multi-hop MAC protocol (MMAC) [5] can be regarded as one of RTS-DTDR protocols, except RTS frames are received omni-directionally. Then, we compare the performance of BAS-DTDR with that of RTS-DTDR and discuss the implications from this lightweight scheme.

A. Performance Model

The throughput is calculated by the proportion of time that a node spends transmitting data packets successfully on average. In this paper, we adopt a discrete Markov chain model which was used in [16], [20] to evaluate the saturation throughput of wireless networks. We also adopt the assumption that each node operate in time-slotted mode, with a time slot τ. If the time slot τ is very small, the performance of the time-slotted protocol is very close to that one of the asynchronous version of the protocol [16], [20]. The period of time during which RTS, CTS, data and ACK frames are transmitted can be depicted as multiples of τ, i.e., t_{rts}, t_{cts}, t_{data} and t_{ack}, respectively. Let $P(S)$, $P(I)$ and $P(C)$ denote the steady-state probability of *SUCCEED*, *IDLE* and *COLLISION*, respectively. Then we have:

$$Throughput = \frac{P(S) \cdot t_{data}}{P(C)T_C + P(S)T_S + P(I)T_I} \tag{5}$$

where T_C, T_S and T_I are the duration of *COLLISION*, *SUCCEED* and *IDLE*, respectively.

From Fig. 4, the steady-state probability of *IDLE* equals:

$$P(I) = P(I) \cdot P_{II} + P(S) + P(C) \tag{6}$$

Noting that $P(S) + P(C) = 1 - P(I)$, thus,

$$P(I) = 1/(2 - P_{II}) \tag{7}$$

The duration of a node in *IDLE* state T_I is 1τ.

From Fig. 4, the steady-state probability of *SUCCEED* can be calculated by $P(S) = P(I) \cdot P_{IS}$. Before deriving the transition probability P_{IS} from *IDLE* to *SUCCEED*, we need to calculate the probability $P_{IS}(r)$ that a node X_i successfully shakes hands with a node X_j which is a distance r away from X_i within a given time slot.

The MAC overhead can also be calculated by:

$$Overhead = \frac{P(S) \cdot t_{ctrl}}{P(C)T_C + P(S)T_S + P(I)T_I} \tag{8}$$

where t_{ctrl} is depicted as time slots which are used by control frames such as RTS, CTS and ACK.

B. Directional Transmission and Directional Reception

We need to calculate the throughput of BAS-DTDR and RTS-DTDR. From the throughput model presented in Section IV-A, we need to calculate the transition probability P_{IS} from *IDLE* to *SUCCEED* first. Fig. 5 indicates that the nodes within the four regions (named 1, 2, 3, 4) around X_i and X_j may cause collisions with X_i and X_j. Since the number of nodes are quite related to the area size if the density is given, we need to calculate the every size of the four areas, which are denoted as S_1, S_2, S_3, S_4, respectively:

$$\begin{aligned} S_1 &= \pi R_t^2 \cdot \theta/(2\pi) \\ S_2 &= \pi R_t^2 \cdot \theta/(2\pi) - R_t^2/2\tan(\theta/2) \\ S_3 &= \pi R_i^2 \cdot \theta/(2\pi) - \pi R_t^2 \cdot \theta/(2\pi) \\ S_4 &= \pi R_i^2 \cdot \theta/(2\pi) - \pi R_t^2 \cdot \theta/(2\pi) \end{aligned} \tag{9}$$

$P_{IS}(r)$ equals the probability that X_i transmits in a given time slot, X_j does not transmit in the same time slot, and none of the nodes within the four regions interferes with the handshake between nodes X_i and X_j. Therefore, we have:

$$P_{IS}(r) = p(1-p) \cdot P_1 \cdot P_2 \cdot P_3 \cdot P_4 \tag{10}$$

Because RTS-DTDR does not prevent interference from neighboring nodes in regions 3 and 4, the handshake might be interrupted at any time. Therefore, the *COLLISION* period T_C lasts from $T_1 = t_{rts} + 1$ till $T_2 = t_{rts} + t_{cts} + t_{data} + t_{ack} + 4$, where the propagation delay is also considered (one propagation delay is 1τ). We also assume that T_C follows a truncated geometric distribution:

$$T_C = (1-p)/(1-p^{T_2-T_1+1}) \textstyle\sum_{i=0}^{T_2-T_1} p^i (T_1 + i) \tag{11}$$

The probability that no nodes in region 1 interferes with the handshake between nodes X_i and X_j is equal to the probability that no node in the area transmits as node X_i does, which can be depicted as:

$$P_1 = e^{-p\rho S_1 \frac{\theta}{2\pi}} \tag{12}$$

For the probability P_2, it must meet the requirement that no node transmits in t_{rts} slots toward node X_j and does not transmit in the slot when node X_i begins to transmit toward node X_j. Therefore,

$$P_2 = e^{-p\frac{\theta}{2\pi}\rho S_2(t_{rts}+1)} \cdot e^{-p\frac{\theta}{2\pi}\rho S_2} \tag{13}$$

P_3 is equal to the probability that no node can interfere with the reception of CTS and ACK frames of node X_i. Hence, we have:

$$P_3 = e^{-p\frac{\theta}{2\pi}\rho S_3(t_{cts}+1)} \cdot e^{-p\frac{\theta}{2\pi}\rho S_3(t_{ack}+1)} \tag{14}$$

In region 4, there is no interference if no node transmits toward X_j when X_i is sending a data frame. Then, we get:

$$P_4 = e^{-p\frac{\theta}{2\pi}\rho S_4} \cdot e^{-p\frac{\theta}{2\pi}\rho S_4(t_{data}+1)} \tag{15}$$

Because each transmitter can choose its receiver with equal probability and the average number of nodes within a region of radius r is propotional to r^2, the probability density function of the distance r between nodes X_i and X_j is $f(r) = 2r$, where $0 < r < R_t$.

Therefore, P_{is} is equal to:

$$P_{IS} = \int_0^{R_t} p(1-p) \cdot P_1 \cdot P_2 \cdot P_3 \cdot P_4 \cdot 2r\mathrm{d}r \tag{16}$$

And the success period T_S is $T_S = t_{rts} + t_{cts} + t_{data} + t_{ack} + 4$. After the corresponding parts are replaced in Eq. (5), the throughput of RTS-DTDR is obtained.

Since $t_{ctrl} = t_{rts} + t_{cts} + t_{ack} + 4$ in RTS-DTDR, similarly we calculate the overhead of RTS-DTDR from Eq. (8).

Since there is no RTS and CTS frames, BAS-DTDR has a narrower bound on T_C (from $T_1 = 1\tau$ to $T_2 = t_{data}+t_{ack}+2$). And the success period time is $T_S = t_{data}+t_{ack}+2$. P_1 keeps the same value as RTS-DTDR. P_2 is equal to the probability that no node transmits toward node X_j within the t_{data} period and does not transmit in the slot when node X_i begins to transmit with node X_j, therefore,

$$P_2 = e^{-p\frac{\theta}{2\pi}\rho S_2(t_{data}+1)} \cdot e^{-p\frac{\theta}{2\pi}\rho S_2} \tag{17}$$

Similarly, we have

$$\begin{aligned} P_3 &= e^{-p\frac{\theta}{2\pi}\rho S_3(t_{ack}+1)} \\ P_4 &= e^{-p\frac{\theta}{2\pi}\rho S_4} \cdot e^{-p\frac{\theta}{2\pi}\rho S_4(t_{data}+1)} \end{aligned} \tag{18}$$

Then after replacing the corresponding parts in Eq. (5), we get the throughput of BAS-DTDR. Since $t_{ctrl} = t_{ack} + 2$ in BAS-DTDR, we calculate the overhead of BAS-DTDR from Eq. (8).

We compare the performance of the RTS-DTDR and BAS-DTOR and present the results in Fig. 6 and Fig. 7.

C. Numerical Results

Fig. 6 shows the saturation throughput and overhead of RTS-DTDR and BAS-DTDR under different node densities (N=10, 20, 30, 40, respectively) when the beamwidth is less than $\frac{\pi}{6}$. The results were obtained under a short data length 40τ. With the increased node density, both RTS-DTDR and BAS-DTDR degrade. The BAS-DTDR has a much higher throughput than RTS-DTDR protocol. The peak value of BAS-DTDR is almost 20% higher than that of RTS-DTDR. One possible reason is that when the beamwidth is very narrow, the interfering nodes are so sparse that they cause nearly no collisions at that time. In this situation, RTS/CTS frames are not neccessary to be used. On the contrary, they only contribute additional overhead on the throughput.

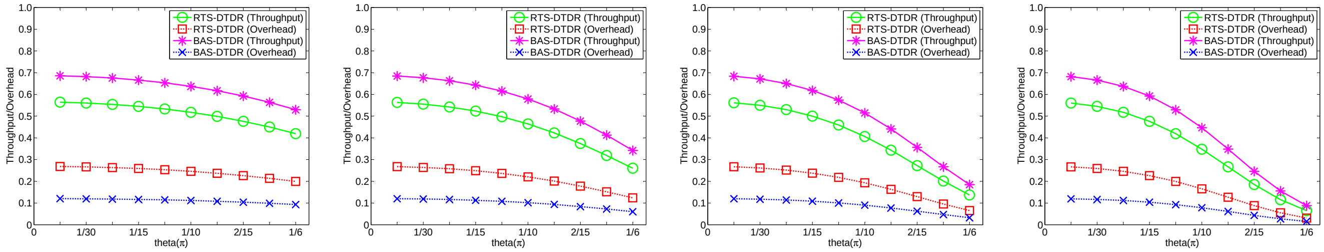
Then we calculate the throughput and overhead under the long data length setting ($t_{data} = 120\tau$) and the results are shown in Fig. 7. Similarly, both RTS-DTDR and BAS-DTDR perform well under a narrow beam (e.g., $\frac{\pi}{15}$). Under this setting, BAS-DTDR still has a higher throughput than RTS-DTDR because it gets rid of the bulky RTS/CTS mechanism. However, when the beamwidth is increased further, the collisions caused by interfering nodes become remarkable, both the throughput of RTS-DTDR and BAS-DTDR degrades. At this time, the throughput of BAS-DTDR drops even faster than RTS-DTDR. Hence, there exists a trade-off between the arisen interfering nodes and the overhead of control frames. For example, in Fig. 7 (b), the equal point of interference and overhead locates at $\theta = \frac{2}{15}\pi$. When $\theta \leq \frac{2}{15}\pi$, BAS-DTDR performs better than RTS-DTDR because the cost of control frames surplus the impact of interfering nodes. However, if the beamwidth is increased further ($\theta > \frac{2}{15}\pi$), interference will play the primary role. Collision avoidance mechanisms should act on the interference in this situation.

D. Discussions

The results in Fig. 6 and Fig. 7 show that, when the beamwidth is decreased, the network throughput grows very fast. The capacity analysis in [15] also proves that the capacity grows with the lessened beamwidth. However, the capacity will not grow arbitrarily high when the beamwidth decreases further and even approaches to zero. Yi et al. [15] have also observed that when the beamwidth is too small, the interference has been fully reduced and there is no further improvement by decreasing the beamwidth of the antennas.

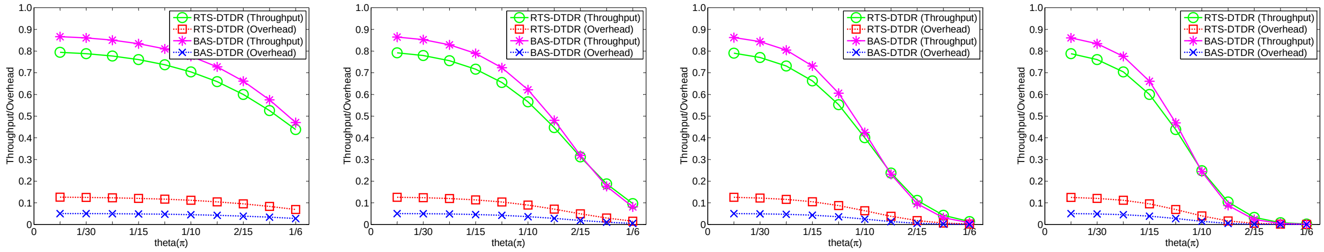
Actually, when the beamwidth is narrow enough (more specifically, less than a certain angle) a transmission can yield a high success probability. As shown in Section III-C, if the beamwidth is less than $\frac{\pi}{12}$ (i.e., $15\,^{\circ}$) and both directional antennas are used at the transmitter and the receiver, then the probability of a successful transmission is greater than 99%. The transmission under this situation can be regarded as a *collision-tolerant* transmission (the collision probability is quite small). Hence, Directional Transmission and Directional Reception should be the best way to use directional antennas. The angle $15\,^{\circ}$ is feasible in most *intelligent* directional antennas. With this condition, the collision avoidance mechanisms, such as RTS/CTS, are not neccessary to be used because they only contribute excessive overhead on the performance.

This collision-tolerant transmission gives us some important implications on MAC design. Directional antennas have different properties, e.g., higher spatial reuse and the smaller interfering region. Although RTS/CTS schemes work well in wireless networks using omni-directional antennas, they



(a) $N = 10$ (b) $N = 20$ (c) $N = 30$ (d) $N = 40$

Fig. 6. Throughput comparison when $p = 0.1, t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 40\tau$ (short data frame)



(a) $N = 10$ (b) $N = 20$ (c) $N = 30$ (d) $N = 40$

Fig. 7. Throughput comparison when $p = 0.1, t_{rts} = t_{cts} = t_{ack} = 5\tau$, $t_{data} = 120\tau$ (long data frame)

cannot mitigate interference caused by directional antennas completely [5]. Thus, the MAC layer design with directional antennas should be started from other different perspectives. For example, when the beamwidth is narrow enough, we may need to turn off RTS/CTS. On the contrary, we should consider other techniques, such as power control and multi-channel schemes to reduce interference.

V. CONCLUSION

This paper studies the performance of wireless networks using directional antennas with a narrow beam. In particular, we examine the probability of a successful transmission under Directional Transmission and Directional Reception. The numerical results show that the interference probability will be quite low if the antenna beamwidth is narrow enough. These results encourage us to design a lightweight MAC protocol which turns RTS/CTS off. The preliminary results prove that the protocol has a higher throughput than the typical MAC protocol based on RTS/CTS. The results also demonstrate that a collision-tolerant transmission is feasible when the beamwidth is narrow enough. One of our future work is to implement the lightweight MAC protocol in real environments.

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