SIMULATION AND IMPROVEMENTS

FOR

COOPERATIVE MAC (COMAC) PROTOCOL

by

Murat Erman

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COOPERATIVE MAC (COMAC) PROTOCOL

APPROVED BY:

Assoc. Prof. Özgür Gürbüz, (Dissertation Supervisor)

....

Assoc. Prof. İbrahim Tekin

....

Assoc. Prof. Albert Levi

....

Asst. Prof. Hakan Erdogan

....

Assoc. Prof. Özgür Erçetin

....

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Abstract

Cooperative communication has been recently proposed for wireless sensor networks for achieving reliable, high data rate communication, eventually decreasing energy consumption at the nodes and extending the lifetime of the sensor network. The benefits of cooperation can be obtained by appropriate design of the medium access control (MAC) protocol. In this thesis, we present a cooperative MAC protocol that enables cooperation of multiple relays in a distributed fashion. It is shown that energy efficiency of the protocol significantly depends on cooperator selection and power assignment. We propose random and intelligent timer models for coordinating access of the cooperating nodes. Next, we consider the contention channel observed during the cooperator selection period and we propose a collision resolution mechanism. We consider two alternatives for cooperative transmissions, and compare the performances of code division based and time division based approaches. The cooperative MAC protocol is further improved by introducing sleep feature for the relay nodes, since the major sources of wasted energy for the cooperative system are idle listening and overhearing. We evaluate the cooperative MAC protocol with all the proposed enhancements in terms of energy efficiency, throughput, average delay and MAC overhead cost and demonstrate the performance improvements.

Özet

İşbirlikli haberleşme, kablosuz algılayıcı ağlarda güvenilir, yüksek veri hızlı haberleşmeye ulaşmak için kullanılan ve algılayıcı düğümlerin enerji harcamasını düşüren ve algılayıcı ağın yaşam süresini artıran bir teknik olarak önerilmektedir. İşbirliğinin faydaları, uygun ortam erişim kontrol (MAC) protokolü dizaynı ile elde edilebilir. Bu tezde, çok sayıda rölenin dağınık bir yapıda işbirliğini sağlayan bir işbirlikçi MAC protokolü önerilmektedir. Protokolün enerji verimliliğinin önemli derecede işbirlikçi seçimi ve güç atamasına bağlı olduğu gösterilmiştir. İlk olarak, işbirlikçi düğümlerin erişimini koordine eden rastgele ve akıllı zamanlayıcı mekanizmaları önermekteyiz. Ardından, işbirlikçi seçimi süresinde görülen çekişme kanalını dikkate alarak bir çakışma çözümlemesi mekanizması önermekteyiz. İşbirlikçi iletimde kod bölmeli ve zaman bölmeli yaklaşımları da incelemekte ve bu iki alternatifin performanslarını kıyaslamaktayız. İşbirlikçi sistemlerin en büyük enerji kaybı kaynaklarının boşta dinleme ve istem dışı dinleme olduğunu dikkate alarak, işbirlikçi MAC protokolünü uyuma özelliği ile geliştirmekteyiz. Bu çalışmada, işbirlikçi MAC protokolünü, tüm önerilen geliştirmelerle birlikte, enerji verimliliği, verim, ortalama gecikme ve MAC paket ek yükü açısından değerlendirmekte ve performans iyileşmelerini göstermekteyiz.

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1 INTRODUCTION

There is an increasing demand on wireless networks. Wireless networks are widely used in every stage of life [1].

Traditional wireless systems are designed to have only one source and one destination. This architecture deteriorates performance of wireless networks in situations with low channel quality. Cooperative communication is designed to overcome this problem in wireless sensor networks [1].

In cooperative communications, nodes in the close vicinity of source node repeat data signal together with the source, in order to provide a cooperative diversity at the destination node [51].

Sensor nodes are battery operated small wireless devices. Battery life is accepted to be the main concern about these devices. Wireless sensor networks are based on cooperative communications, in order to take advantage of cooperative diversity. As a result of low power capabilities, sensor nodes have limited communication range, and hence require cooperative communication schemes more often [1].

Diversity gain obtained at the destination demands increased energy consumption due to participation of neighbouring nodes into the communication [1]. In order to extend battery life of sensor nodes, cooperator selection and order should be determined carefully [41]. Various researchers developed MAC layer cooperative communication algorithms for selecting optimal relay nodes [19,21,24,25,32,34,43,49]. Two important goals of designing MAC layer algorithm for cooperative communication is cooperator selection and power assignment. In addition, order of cooperating relay nodes substantially affect energy performance of the cooperative system. Optimal timing of cooperation decision announcements would result in optimal order of relay nodes. This timing should be handled carefully in order to minimize collisions and packet loss.

Sensor nodes spend energy even if they are idle. Overhearing and idle listening decrease energy efficiency of the node [49,53]. New MAC protocols are being developed to keep the sensor nodes in sleep state when they are not in active communication.

Consequently, design of an optimal cooperative network necessitates effective determination of medium access decision and timing of relay nodes. Moreover, further reduction in energy consumption can be achieved via adjusting radio states of the nodes [49,53].

1.1 Thesis Contributions

- The following features were added to COMAC protocol proposed in [43].
- Distributed relay selection and power assignment algorithm is implemented in the COMAC protocol. Relay selection order problem of this cooperative protocol is analyzed. Timer mechanisms for cooperation announcement time are proposed and compared.
- Cooperative MAC protocol is further improved by introducing collision resolution of relay node cooperation messages.
- Two multiple access techniques (CDMA,TDMA) are implemented and compared for data repeat phase of cooperative transmission.
- Sleep/wakeup mechanisms are introduced for the COMAC protocol, so that nodes are set to sleep when they are idle, not participating in cooperation.

- The performance of the COMAC protocol was analyzed considering energy consumption, throughput, delay and overhead for evaluating the effects of all added features.
- Computational energy consumption stemming from cooperation decision algorithm processing is also calculated and presented.
- COMAC protocol was tested under scenarios where multiple source nodes contend for sending information to a common destination.

1.2 Thesis Organization

This thesis is organized as follows:

In chapter 2, background on wireless sensor networks and cooperative communications is presented. A literature survey on cooperative communications and MAC level protocol design is also presented in this chapter. In chapter 3, a novel cooperative MAC layer protocol design is explained in detail. Centralized and distributed adaptive relay selection and power assignment mechanisms are introduced here. Timer designs for cooperation decision announcement of relay nodes are also analyzed in this chapter. In addition, different multiple access techniques (CDMA,TDMA) are discussed. Finally, sleep model modification over designed MAC protocol is explained. In chapter 4, results and performance analysis of proposed protocols, designs and architectures are analyzed. In chapter 5, conclusions and discussions are presented.

2 BACKGROUND

In cooperative Wireless Sensor Networks, the signal of a source node is repeated by neighbouring nodes in the close vicinity of the source node. The overall process in in two phases. In Phase-I, source node sends the signal. If cooperation is necessary, selected relays repeat this signal together with the source in Phase-II. This way a transmit diversity is achieved at the destination node.

2.1 Wireless Sensor Networks

A wireless sensor network (WSN) is composed of spatially distributed autonomous sensors to monitor physical or environmental conditions, such as temperature, sound, vibration, motion etc. WSNs are widely used in military, environmental, medical, industrial and home applications. [1]. Typically a wireless sensor device has four main parts: Sensor, Processor, Transceiver and Power Source. Sensor nodes are small battery powered devices and the main concern for sensor nodes is the energy consumption. Battery life limits the lifetime of the network, and replacing the battery of a sensor node is mostly impractical. For this reason, there is extensive research on energy efficiency of WSNs.

2.2 Cooperative Communications

As the energy consumption is the main concern, sensor nodes are characterized with low power capabilities and low transmission range. These limitations make sensor nodes intolerant to imperfections in wireless medium. Due to multipath fading, shadowing and path loss effects, data transmission may result in failure and retransmission of data might be needed which is quite expensive in terms of energy consumption. Cooperative communications phenomenon address the need to increase throughput and energy efficiency of the system especially in bad channel conditions. The cooperative communication theory is based on participation of the neighbouring nodes, that overhear the data signal, into the communication of a source node and a destination node. These neighbouring nodes are called as relay nodes, and the operation of using such nodes for cooperative data transmission is called as relaying of information. The early research on cooperative communications go back to works of Van der Meulen[2], and Cover and El Gamal[3], where the relay channel and a number of relaying strategies are defined. The aim of cooperation is to provide cooperative diversity at the destination node. Diversity gain of cooperative systems is analyzed in [4], and [5]. In works [6,7] energy efficiency of cooperative systems is demonstrated. It has been shown that Multi-Input Multi-Output (MIMO) systems require lower transmission energy for same throughput than Single-Input Single-Output (SISO) systems[27]. Cooperative systems are based on energy efficiency of MIMO systems. However, it is not feasible to construct a multi-antenna system on a sensor node, because of size limitations. If individual single relay nodes cooperate, a cooperative MIMO system can be emulated and energy efficiency of MIMO systems can be achieved. In cooperative systems, independent fading channels are combined at the receiver. This way a spatial diversity is achieved. Coherent combining of the independent signals increases SNR at the receiver and mitigates the effects of fading. The received signal can be combined in several ways. The major diversity combining techniques are Maximal Ratio Combining (MRC), Selection Combining(SC), Equal Gain Combining(EGC) and Square Law Combining(SLC). If complex channel gain is known at the transmitters, MRC can be used [28,29]. However if complex channel gain is not available, space-time codes are required [30]. In cooperative communications, there are three main cooperation protocols [31]. In estimate and forward, relay node sends an estimate of data signal received from source, to destination. When amplify and forward is used, relay node amplifies the source signal and sends to destination. This technique is useful when source-relay link is comparable to relay-destination link. If relay nodes are in close vicinity of source node, then relay node can successfully decode the source signal and then forward to destination. This protocol is called as decode and forward [47]. In our work, we assume that relay nodes are close to source node, and hence we will use decode and forward technique.

2.3 Relay Selection

In cooperative communications, relay selection affects the energy efficiency of the cooperative system. Energy consumption of the cooperative system depends on selected cooperation set and assigned power levels to cooperating relay nodes. Optimal cooperator selection and power assignment requires an efficient algorithm in MAC layer. Several works address this problem. In cooperative communications, MAC layer protocol seeks an optimal set of relay nodes, tries to determine the number of nodes, select the suitable nodes, allocate resources between these cooperators. The ultimate goal is to increase reliability of the channel, to increase transmission coverage and reduce energy consumption per successful data transmission. Existing MAC protocols consider wireless networks with a predefined structure and lack to support a cooperative system with several hops [32-36]. In [8-12], inclusion of relays into to cooperation is not controlled. All suitable relays are accepted to cooperate. These are more likely to be examples of a centralized architecture. In [13-15], number of relays is predefined, and in [16-18] instantaneous channel statistics are used for relay actuation. The MAC layers proposed in [19-26] do not analyze the energy cost of the system or the effect of the overhead of MAC protocol. In [44], authors define a cooperative MAC protocol that provides significant throughput enhancements, using distributed relay selection and power assignment. This protocol is scalable, adaptive and aims to minimize total energy consumption of cooperative system. However, this protocol does not define how to determine effective order of cooperating nodes precisely. In addition, an important performance degrading factor of cooperative system: collision resolution mechanism is also not implemented in this work. Recent studies also include sleep/wakeup mechanism for cooperating nodes [49]. This mechanism reduces energy consumption of cooperative system significantly. This thesis, defines means for ordering relay nodes, modifies the protocol by adding collision resolution and provides sleep/wakeup mechanism to existing protocol.

3 COOPERATIVE MAC FOR WSNs

In this chapter, the cooperative MAC protocol defined in [43,44] is explained and new functionalities such as collision resolution, and sleep/wakeup mechanism are introduced to the protocol. This chapter is organized as follows:

In section 3.1, COMAC operation is explained considering a single relay. In section 3.2, COMAC protocol with multiple relays is defined. In section 3.3, relay selection and power assignment mechanism is explained in detail. When COMAC with multiple relays is used, each relay should be able to decide for its inclusion in cooperation and assign its related power level individually, resulting in a distributed manner. When multiple relays try to participate in cooperation, the order and timing of cooperation requests of relay nodes should be defined carefully so as to provide energy efficency and avoid collisions. In order to achieve this purpose, in section 3.4, timer designs for cooperation announcement of relay nodes are proposed. The order of cooperators determines the energy efficiency of the cooperative system. Collision may be seen in the network depending on location of relay nodes and the timing of cooperation announcements, in order to overcome this problem, in section 3.5, collision resolution mechanism for cooperation announcements is defined. Collision resolution affects the performance of the cooperative system, COMAC protocol is extended to provide collision resolution mechanism. Reduced energy consumption is aimed at the cost of increased protocol overhead. In section 3.6, cooperation mode of relay nodes is discussed. Cooperating relay nodes can send data signal copy to destination simultaneously using CDMA or in consecutive time slots using TDMA. In section 3.7, sleep/wakeup mechanism is explained. The relay nodes can go to sleep state when they do not participate in cooperation. The aim here is to reduce overall energy consumption of the cooperative system by avoiding idle listening and overhearing energy consumption.

3.1 COMAC Operation

In this work, we explain COMAC operation [44]. There are source, destination and relay nodes in the medium as depicted in Figure 3.1. COMAC protocol is based on existing MAC protocol, and uses same mechanism for reserving medium. Source node starts transmission with sending a Request-to-Send in Cooperation (C-RTS) message. Destination node replies with a Clear-to-Send in Cooperation (C-CTS) message. The relay node sends an Available-to-Cooperate (ACO) message to announce that it can participate in cooperation. When source node receives ACO message, sends data signal. This data packet is named as $C-DATA_I$ and this part of cooperative transmission is called as phase-I. Then source and relay nodes together repeat data signal. This second data packet is called as $C-DATA_{II}$ and this part of cooperative transmission is called as phase-II. Destination node replies back with an Acknowledge in Cooperation (C-ACK) message. This message completes cooperative transmission.

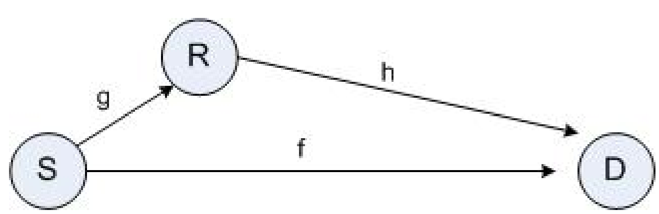

Figure 3.1: System Model

3.2 COMAC with Multiple Relays

In our system we have one source, one destination and N relay nodes. The aim is to find the group of relays that minimizes the total energy consumption to send one successful bit to destination, under a given average BER level constraint. As stated before, there are N relay nodes and our system should select a subset of these nodes, and define suitable power levels to selected relay nodes in order to satisy power and BER requirements.

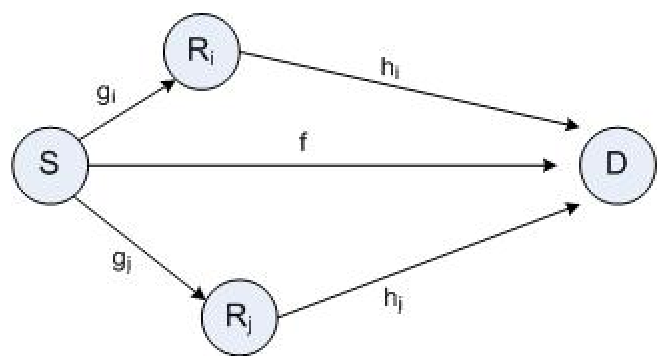

Figure 3.2: System Model with multiple relays

COMAC is designed to provide cooperative transmission. Relay nodes are utilised for achieving a successful data transmission. The model was introduced for one relay only in previous section. Here, we explain COMAC operation to support multiple relays. When more than one relay is used, relay selection mechanisms should be defined for the system.

When source node sends C-RTS message, destination node understands that a data transmission will begin soon. Destination node replies back with an C-CTS message.

A neighbouring node that receives both C-RTS and C-CTS is a candidate relay for cooperative transmission. All candidate relays make a decision to participate cooperation or not. If a relay node decides to cooperate, announces this decision with an ACO message. COMAC protocol reserves a predefined duration for relays to announce their decision. This duration is called as ACO-epoch. ACO-epoch is configurable and calculates as $K(T_{ACO} + T_{SIFS})$, where T_{ACO} is the duration to send an ACO packet successfully, and T_{SIFS} is the duration of one short interframe spacing. Here the parameter K defines and limits the number of cooperators that can participate in cooperation [43].

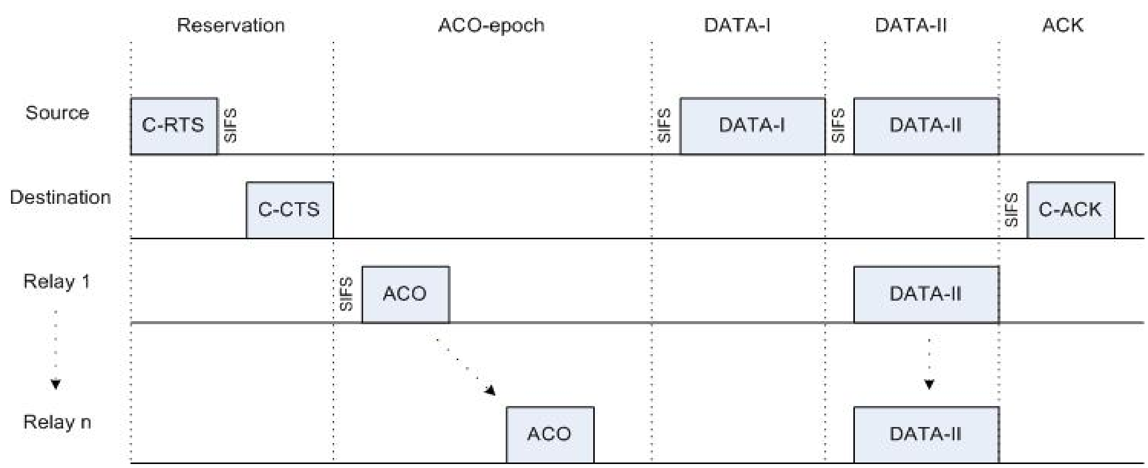

Figure 3.3: COMAC frame sequence

Relay selection is an integral part of COMAC. Relay selection can be performed in a centralized or distributed manner, and can be based on an algorithm or random selection. Relay selection mechanisms will be discussed in next sections.

If relay selection process ends up with failure, source node reverts back to direct transmission, when ACO-epoch ends. Source node sends an INFO message to announce this decision.

If source node decides to continue with cooperative transmission, sends $DATA_I$ packet, selected relay nodes repeat this packet together with source node in phase 2 of data transmission. Relay nodes should not use maximum available power level for cooperation in order to provide energy efficiency. Power assignment of relay nodes is done in several mechanisms, which will be discussed in next sections.

The destination node replies back with an ACK message, if data is successfully received. Transmission ends successfully when source node receives this ACK packet. If destination cannot receive the data packet successfully, then it does not send ACK packet. If source node does not receive ACK packet within a predefined time period, concludes that transmission ended up in failure and triggers retransmission procedure.

NAV Timer

The relay nodes that do not participate in cooperation set a timer and do not access the medium until this timer expires.

The Network Allocation Vector (NAV) is virtual carrier sensing mechanism used with wireless network protocols such as IEEE 802.11 [48]. The virtual carrier sensing is a logical abstraction which limits the need for physical carrier sensing at the air interface in order to save power. The MAC layer frame headers contain a Duration field that specifies the transmission time required for the frame, in which time the medium will be busy. The stations listening on the wireless medium read the Duration field and set their NAV, which is an indicator for a station on how long it must defer from accessing the medium

NAV timer upon receiving RTS : Direct transmission is assumed here, and cooperative transmission is not taken into account, type of transmission is not decided yet. NAV timer is set as :

D_{C-RTS} = *3x*T_{SIFS} + T_{C-CTS} + T_{DATA} + T_{ACK} + *3**$T_{max.prop.delay}$

NAV timer upon receiving CTS : Type of transmission still not decided. NAV timer is set as :

D_{C-CTS} = *2x*T_{SIFS} + T_{DATA} + T_{ACK} + *2**$T_{max.prop.delay}$

NAV timer upon receiving ACO : Cooperative transmission is certain now. NAV timer is set as :

$D_{ACO} = T_{ACO-epoch} + T_{ACO}$

NAV timer upon receiving INFO : This packets informs nodes that source node will revert back to direct transmission. NAV timer is set as :

$D_{INFO} = 2xT_{SIFS} + T_{DATA} + T_{ACK} + 2{*}T_{max.prop.delay}$

NAV timer upon receiving $DATA_I$ - cooperative transmission : NAV timer is set as :

$D_{C-DATA_I} = 2xT_{SIFS} + T_{DATA} + T_{ACK} + 2{*}T_{max.prop.delay}$

NAV timer upon receiving $DATA_I$ - direct transmission : NAV timer is set as :

$D_{C-DATA_I} = T_{SIFS} + T_{ACK} + T_{max.prop.delay}$

NAV timer upon receiving $DATA_{II}$: NAV timer is set as :

$D_{C-DATA_I} = T_{SIFS} + T_{ACK} + T_{max.prop.delay}$

Here, T_{SIFS} is the time needed for a radio to switch from transmitting mode to receive mode [48]. $T_{max.prop.delay}$ is the maximum propagation delay between any two stations in the network.

COMAC frame sequence and related NAV timers are depicted in Figure 3.4.

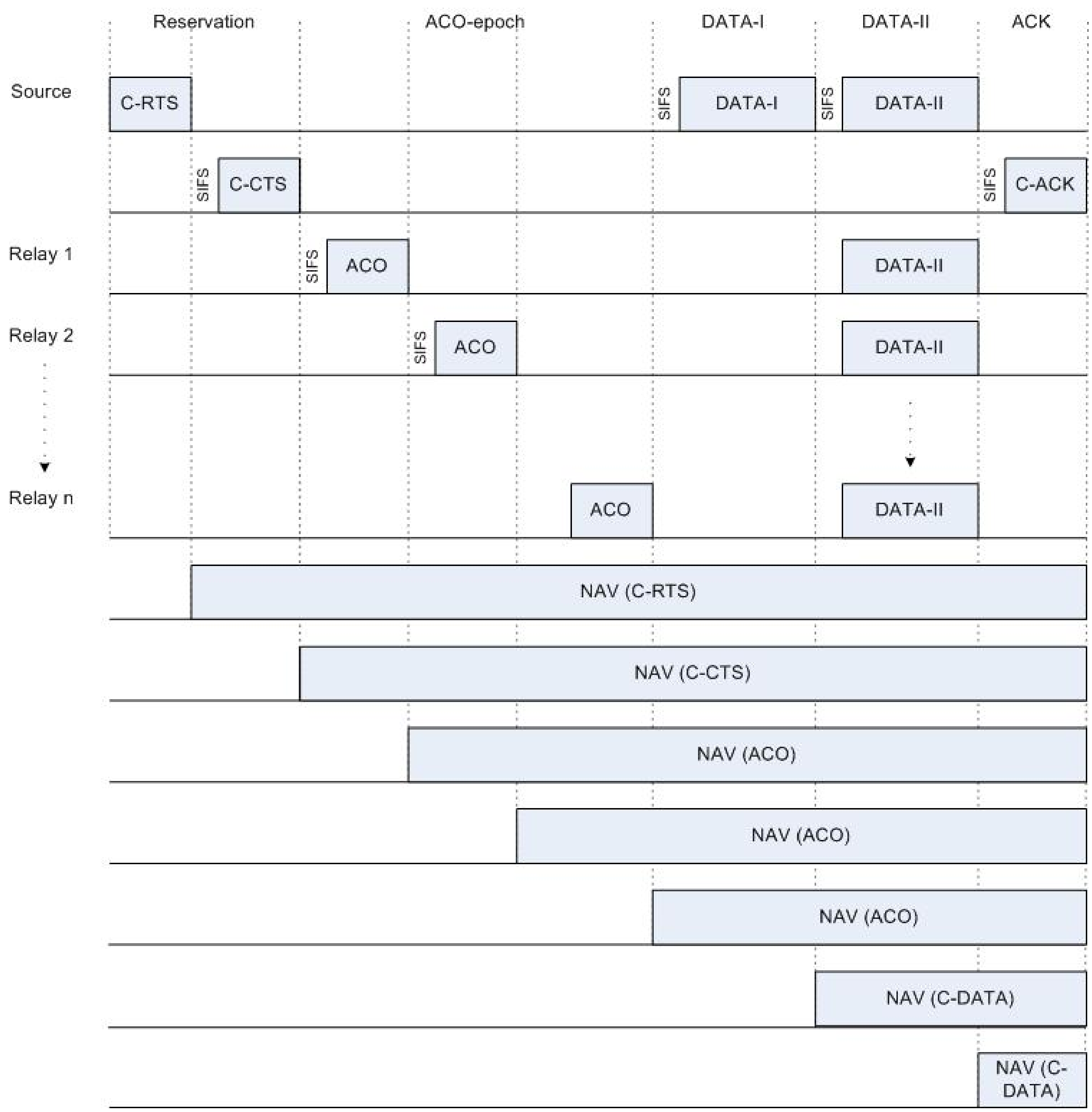

Figure 3.4: COMAC frame sequence and related NAV timers

3.3 Optimal Relay Selection and Power Assignment

COMAC is based on participation of neighbouring nodes into the data transmission. All relay nodes, that receive C-RTS and C-CTS are nominated as candidate relays. However, still it is not certain, which relays will be selected and what level of transmission power they will use. A relay selection and power assignment algorithm is needed to complete ACO-epoch successfully. Various relay actuation meachanisms can be incorporated into COMAC. In this work, we analyze three different relay selection and power assignment methods: COMAC with random cooperator selection (R-CS), COMAC with optimal cooperator selection (O-CS) and COMAC with distribued cooperator selection and power assignment (D-CSPA)

If there are N neighbouring relays in the neighborhood of source and destination, and cooperation set is composed of r relays, then there are $\binom{N}{r}$ possible cooperation sets: $C_{r,0}$, $C_{r,1}$, ..., $C_{r,\binom{N}{r}}$ [43]. Our cooperative system first checks whether cooperation is needed or not, then selects the relays during an ACO-epoch and finally sends the data to destination. In case of cooperative scenario, data signal is sent to destination in two phases : In phase 1, S transmits its signal with an energy-per-bit level of E_b Joules/bit. In phase 2, the nodes in the selected cooperation set, say $C_{r,j}$, cooperatively transmit the decoded-and-regenerated signal to D through orthogonal channels. Here we assume that each cooperator R_i in the cooperator set $C_{r,j}$, can adjust its transmit power level to $\rho_{r,j}(i)*E_b$ J/b, where $\rho_{r,j}(i)$ denotes the relay's relative power level with respect to the power level of the source, $0 \leq \rho_{r,j}(i) \leq 1$, $R_i \in C_{r,j}$. This way we assign a power vector ρ_j to our cooperation set. Each member of this vector is the relative power level of corresponding relay node in the cooperation set. In our system model, independent Rayleigh fading applies to direct channel and neighbouring relay channels. Channel coefficient for these channels are f, g_i, h_i respectively. Mean channel gains are σ_f, σ_{g_i} and σ_{h_i} respectively. Assuming that all channels have additive white Gaussian noise with variance N_0, instantaneous SNR values for SD, SR and RD channels are found as follows : $\gamma_f = E_b/N_0 {*} f^2$, $\gamma_{g_i} = E_b/N_0 {*} {g_i}^2$, $\gamma_{h_i} = E_b/N_0 {*} {h_i}^2$. Additionally, we assume that average channel statistics are given as follows : $\bar{\gamma}_f = E_b/N_0 {*} f^2$, $\bar{\gamma}_{g_i} = E_b/N_0 {*} g_i^2$, $\bar{\gamma}_{h_i} = E_b/N_0 {*} h_i^2$.

Our model is based on a target average bit-error-rate, BER, level. We try to find the set of relays nodes that minimizes the total energy cost. As it can be seen from (3.8), minimizing total energy cost depends on assigning optimal relay power levels. This problem is solved by [43] and the optimal relative power assignment for the cooperative system with

$$\rho^*_{r,j} = \frac{1}{\bar{\gamma}_f}\Big(\Omega(C_{r,j}, \bar{\gamma}_f) \prod_{R_k \in C_{r,j}} \frac{\sigma_f^2}{\sigma_{h_k}^2}\Big)^{1/r} - \frac{\sigma_f^2}{\sigma_{h_k}^2 \bar{\gamma}_f} \tag{3.1}$$

where,

$$\Omega(C_{r,j}, \bar{\gamma}_f) \triangleq \frac{\Lambda(r, \bar{\gamma}_f) Q(C_{r,j})}{P_{th} - \bar{P}_b(\bar{\gamma}_f) Q'(C_{r,j})} \tag{3.2}$$

$$\Lambda(r, \bar{\gamma}_f) \triangleq \frac{1}{\pi} \int_0^{\pi/2} \frac{(\sin\phi)^{2(r+1)}}{\sin^2\phi + \bar{\gamma}_f} \tag{3.3}$$

$$\bar{P}_b(\bar{\gamma}_f) \triangleq \frac{1}{2}\Big(1 - \sqrt{\bar{\gamma}_f/(1+\bar{\gamma}_f)}\Big) \tag{3.4}$$

$$Q(C_{r,j}) \triangleq \prod_{R_i \in C_{r,j}} exp(-\gamma_{th}/\bar{\gamma}_{g_i}) \tag{3.5}$$

$$Q^{'}(C_{r,j}) \triangleq 1 - \prod_{R_i \in C_{r,j}} exp(-\gamma_{th}/\bar{\gamma}_{g_i}) \quad (3.6)$$

In these equations, Q is the probability that all cooperators in cooperation set can successfully decode and regenerate the source transmission, and $Q^{'}$ is the probability that not all cooperators in cooperation set can successfully decode and regenerate the source transmission [43]. $\bar{P}_b(\bar{\gamma}_f)$ is the average BER of the direct SD channel, assuming binary phase shift keying, BPSK, modulation. P_{th} is the average BER target. Proof of this equation can be found in [43].

This problem is solved via an iterative method and resulting procedure is summarized in Algorithm 1 [43].

Algorithm 1 Optimal power assignment

Relay set: $C_{r,j}; C_j = C_{r,j}; k =\mid C_j \mid; F = \{\emptyset\}$ **while** $k \neq 0$ **do**

  for $R_i \in C_j$ **do**

    Compute $\rho^{*}_{r,j} for C_j via equation (3.1)$ **if** $\rho^{*}_{r,j} > 1$ **then**

      | $\rho^{*}_{r,j} = 1$ $F \leftarrow F \cup R_i$

    end

  end

  $C_j \leftarrow C_j - F; k =\mid F \mid; F = \emptyset$

end

Using this algorithm 1, optimal power assignment values can be calculated for relay nodes in a given cooperation set. However, there are $\binom{N}{r}$ possible cooperation sets, and only one of them minimizes the total energy cost. The search for the optimal cooperation set is assured with following inequality [43]:

$$\sum_{R_i \in C_r} \rho_r^*(i) - \sum_{R_i \in C_{r+1}} \rho_{r+1}^*(i) < \frac{E_t + 2E_r}{Eb} \tag{3.7}$$

This process is described in Algorithm 2 in [43]. In this algorithm, a relay node is added into to cooperation set. If cooperation set is not feasible, then another relay is added to the cooperation set. If existing cooperation set is feasible (i.e. all power assignment value are lower than 1), then energy cost of the inclusion of the next relay into the cooperation set is analyzed via Equation (3.7). If Equation (3.7) is satisfied, then it is concluded that inclusion of the new relay does not decrease the energy cost of the system, and hence new relay is not added to the existing cooperation set.

This method is centralized, since the computation of ρ^* requires the channel statistics of all relay nodes in the cooperative system. Implementing this model, necessitates that all channel information is available at a central node [43].

Sharing of all channel statistics requires plenty of information to be exchanged between nodes, which is not efficient in terms of bandwidth and energy [43]. For this reason, a distributed joint cooperation set selection and power assignment method is proposed in [43]. In this algorithm, relay nodes announce their cooperation decision using ACO messages, and each relay makes its own decision based on received RTS/CTS/ACO messages. This distributed algorithm is summarized in Algorithm 3:

Algorithm 2 Distributed algorithm

```
if γ_{g_i} ≥ γ_th then
    r = 0, Decision = ∅ while Decision = ∅ do
        if an ACO from R_l is received then
            r=r+1, C_r ← C_{r−1} ∪ R_l Compute ρ*_r(j), ∀R_j ∈ C_r via Algorithm 1 if ρ*_r(j)
            is not feasible, i.e., ∃R_j ∈ C_r s.t. ρ*_r(j) > 1 then
                Decision=Cooperate
            else
                if (3.7) is satisfied then
                    Decision=Do not cooperate
                else
                    if ε_{ρ*_r} < ε_{ρ*_{r−1}} then
                        Decision=Cooperate
                    else
                        Decision=Do not cooperate
                    end
                end
            end
        end
    end
end
```

The operation of this algorithm is further described in next section.

In our energy consumption model, we look in detail into the energy consumed by source, relay and destination nodes while sending and receiving data signal. Energy consumed by transmitter and receiver circuitries is also taken into account. Assuming all nodes in the network have identical transmitter and receiver circuitries with power consumption levels of w_t and w_r, energy cost per bit spent at transmit and receive circuitries can be calculated as E_t=w_t/r_b and E_r=w_r/r_b, respectively.

Here, each node transmits at a constant bit rate of r_b, with no rate adaption. While calculating energy, we use an energy-per-bit cost model. We calculate the amount of energy needed to successfully transmit one bit of data signal to destination. We assume that the source node always transmits with its maximum available energy-per-bit level, E_b. E_b is calculated as $E_b = \epsilon_{t\alpha} d^{\alpha}$, where $\epsilon_{t\alpha}$ is the energy-per-bit-meter$_\alpha$ at the transmit amplifier and α is the path loss coefficient. Given a predetermined average BER target (P_{th}) and maximum transmit energy level (E_b), d represents the maximum source-destination separation that allows for successful communication. Here we work with d values such that SD direct transmission is not possible. Moreover, relay nodes that contribute to data transmission in phase 2, spend $\rho_{r;j}(i)$*E_b at transmit amplifiers [43].

Based on these assumptions and findings, the total energy-per-bit cost of cooperative system is given as :

$$\varepsilon_{r,j}(\rho_{r,j}) = (1 + \sum_{R_i \in C_{r,j}} \rho_{r,j}(i) * E_b + (r+1) * E_t + (2r+1) * E_r) \tag{3.8}$$

where $C_{r,j}$ stand for the cooperation set and $\rho_{r;j}$ stands for the power vector of the cooperating relays. In this formula we have the energy consumed in the transmit amplifiers of source and cooperating relays nodes, and transmit and receive energy consumptions in source, relay and destination nodes [43].

3.4 COMAC with Relay Selection and Power Assignment

3.4.1 COMAC with Random Relay Selection

R-CS is a centralized algorithm. Relay selection and power assignment is performed by a central node. When R-CS is used, source node selects a relay node randomly. If average BER threshold cannot be satisfied with the selected cooperator, another relay node is randomly selected and added to the cooperator set, until the average BER result is achieved. R-CS assigns maximum available transmission power levels to cooperating nodes, ($\rho_{r,j} = 1$). R-CS algorithm is mainly discussed in previcous section. R-CS is an implementation of C-CSPA. C-CSPA requires channel statistics of all relay nodes in order to calculate optimal cooperation set and power assignment values [43]. If such information is not present, then relay nodes may be selected on a random basis. In this implementation, when a relay is to be added to the cooperation set, a random number is generated by source node, and related relay node is added to the cooperation set.

3.4.2 COMAC with Optimal Relay Selection

O-CS uses Algorithm 2 in [43], for relay selection. O-CS has the same structure with C-CSPA. C-CSPA is the optimal solution for cooperator selection. Hence, O-CS algorithm finds optimal cooperation set but maximum transmission power levels are assigned to relay nodes. This centralized architecture, uses fixed power levels ($\rho_{r,j} = 1$) for the cooperators. This relay selection algorithm is implemented in order to isolate the effect of power assignment mechanism which will be described in next subsection. When performance of this algorithm is compared with performance of the next described algorithm, effect of defined power assignment algorithm can easily be seen, since both algorithms have same cooperator selection mechanism. Additionally, when results of this algorithm is compared with results of R-CS, effect of cooperator selection can easily be seen, since both algorithms have same power assignment policy.

3.4.3 COMAC with Optimal Relay Selection and Power Assignment

In this section we explain distributed joint cooperation set selection and power assignment (D-CSPA) method. This method is distributed, which means that each node makes its own decision to cooperate or not. When source and destination relays exchange control packets, neighbouring relays that hear these control packets analyze the transmission scheme. If direct transmission is not enough and cooperation is necessary, each relay computes its feasibility to cooperate. Each relay node computes the required power allocation via (3.1). If a relay node concludes that it should participate in cooperation, it becomes a candidate relay for cooperation and such a candidate relay node should announce its decision to neighbouring nodes. Another matter of concern is the order of announcements. Candidate relay nodes should announce their availability in an order based on channel quality. We can summarize the distributed algorithm as follows [43]: When source and destination relays exchange control packets, neighbouring relays that hear these control packets analyze the transmission scheme. If direct transmission is not enough and cooperation is necessary, each relay computes its feasibility to cooperate. Each relay node computes the required power allocation via (3.1). If a relay node concludes that it should participate in cooperation, it becomes a candidate relay for cooperation and such a candidate relay node should announce its decision to neighbouring nodes. Another matter of concern is the order of announcements. Candidate relay nodes should announce their availability in an order based on channel quality. We can summarize the distributed algorithm as follows :

- Neighbouring relays receive RTS and CTS. Upon receiving CTS, in case where direct transmission is not enough, each relay computes its power allocation vector and timer to wait before informing other nodes.

- Assuming that timer for R_1 expires first, R_1 relay node sends an ACO packet. This packet includes the relative power assignment vector $\rho^*_{1,1}$. R_1 also informs other nodes about its channel statistics, σ_{g_1}, σ_{h_1}. Now, inside the cooperation set there is only one relay, R_1.

- When other relays hear the ACO message from R_1, they assume that R_1 will exist in cooperation set and reconsider their decision and recalculate relative power assignment vector based on the information received from R_1. If previous cooperation set is not feasible or if total energy-per-bit cost of the system can further be decreased by participation of R_i into the cooperation, relay R_i decides to cooperate. Assuming next candidate relay in order is R_2, now R_2 sends its availability to cooperate.

- Upon receiving the ACO message from R_2, each candidate relay will have latest cooperation set, relative power assignment vector for cooperation set and channel information (σ_{g_1}, σ_{h_1}, σ_{g_2}, σ_{h_2}) of relays existing in the cooperation set. Then each candidate relay applies the same procedure described in step 3 and final cooperation set is found in an iterative manner.

- This procedure continues until ACO epoch ends. If no relay nodes available for cooperation, or in case the average BER requirement cannot be satisfied with exiting relay nodes, cooperation is aborted.

- During this procedure, if a candidate relay receives an ACO message from one of the other candidate relay nodes and changes its decision to not to cooperate, then it discards its ACO packet, cancels ACO timer and goes to idle state.

The described D-CSPA algorithm is implemented within cooperative MAC protocol. There are three main parts: i) Reservation stage, where cooperative data transmission request is made by the source node, ii) ACO epoch, where the announcements of the candidate relays are sent and the cooperation set is formed and power levels are assigned in accordance with the D-CSPA algorithm, and iii) The cooperative data transmission stage, which includes phases 1 and 2 of cooperation. The operation of the COMAC protocol with D-CSPA algorithm can be summarized as follows:

Cooperative transmission starts with RTS/CTS control packet exchange. The source node sends C-RTS and reserves the medium. The relay and destination nodes check whether they can successfully decode the message from source. At this point, relay and destination nodes have both instantaneous channel statistics of SR and SD channel respectively. Relay and destination nodes can estimate average SNR values for SR and SD channel, $\bar{\gamma}_{g_i}$ and $\bar{\gamma}_f$. At this point, relay nodes decide whether they are inside decoding region by comparing average SNR estimate for SR link with SNR threshold. If average SNR estimate for SR link is greater than SNR threshold, then relay node decides that it can successfully decode data signal from source and hence it is a candidate for cooperation. However, keep in mind that relay nodes do not know whether direct transmission is enough or cooperation is needed, at this instance. Similarly, destination node uses average SNR estimate to check whether source is inside decoding region. This decision is the main criteria for the necessity of cooperation. If average SNR estimate of SD link is less than SNR threshold value, then destination concludes that direct transmission is not enough and cooperation is needed.

When C-RTS is analyzed, destination node knows whether direct or cooperative transmission will be used and relay nodes are certain whether they can cooperate or not. In next step, destination node sends C-CTS. Average SNR value of SD link also exists in this message, so that relay nodes get this information when they receive C-CTS. Upon receiving C-CTS, source node makes an estimate of average SD SNR and concludes whether direct transmission is sufficient. If cooperation is needed, source node should wait for ACO messages of candidate relays and starts a timer proportional to T_{aco}. Meanwhile, relay nodes extract two important information from C-CTS message : Necessity of cooperation and average SNR of SD link. If cooperation is needed, each candidate relay node R_i, computes the relative power assignment value ρ(i) using (3.1). Additionally, each candidate relay node also calculates a timer proportional to T_{aco}. The purpose of this timer is to differentiate between relays and hence to avoid collision of ACO packets from different relays. ACO packet is sent when this timer expires. Each ACO packet includes most recent cooperation set, average SNR of SD link and average SNR of SR and RD links of each and every relay node that already informed that it will participate in cooperation by sending ACO packet.

Each candidate relay node, that receives this first ACO packet, reads existing cooperation set, average SNR values and relative power assignment value of the relay node in cooperation set and reconsiders its decision of cooperation. If existing cooperation set already satisfies BER requirement, then this relay checks whether it can decrease the energy-per-bit cost of the cooperative system. If participation of this new relay further decreases the energy cost, then relay decides to cooperate. Moreover, if existing cooperation set does not satisfy BER requirement, then this new relay decides to cooperate without checking energy requirements. Each candidate relay node, that receives this second ACO packet, can be in two states : If relay already sent ACO, then it will certainly participate in cooperation. If such a relay receives ACO, just reads the existing cooperation set, power assignment vector and learns its new relative power assignment value. If relay that receives ACO did not send its ACO yet (ACO timer is still running), then it reconsiders its cooperation decision as described above. If existing cooperation set does not satisfy BER requirement or if existing cooperation set satisfies BER requirement but energy-per-bit cost of the cooperative system can be decreased when this relay joins cooperation, then this relay does not change its cooperation decision. In such a case, this relay only adds itself to the cooperation set, modifies relative power assignment vector and starts its ACO timer again. If existing cooperation set satisfies BER requirements and inclusion of this relay node does not further decrease energy-per-bit cost of the system, then this relay node decides not to cooperate, cancels ACO timer and goes to idle state. Search for the optimal cooperation set is performed in such an incremental way during ACO epoch. ACO packets are quite crucial for D-CSPA algorithm and ACO collisions should be avoided in order to find best cooperation set. The introduced ACO timer is used here to differentiate between candidate relays. This timer may be based on relative power assignment value of the relay, SR and RD channel characteristics of the relay, or a combination of both, or can also be based on random values. Selecting best ACO timer value to avoid collision is also analyzed in following chapters.

At the end of ACO epoch, if optimal cooperation set is found, source starts cooperative transmission by sending data packet in phase 1. Relays receive and copy this packet. In phase 2, the source and nodes in the cooperation set cooperatively transmit the data packet to the destination node over orthogonal channels at the assigned optimal power levels. When destination successfully receives data packet sent at phase 2, acknowledges the data transmission with a C-ACK packet. Source node receives this C-ACK packet and cooperative transmission is completed in success. If destination cannot receive data packet in phase 2, and accordingly does not send C-ACK packet, and source does not receive C-ACK packet, then source node starts retransmission of the data packet. However, if a suitable cooperation set cannot be found at the end of ACO epoch, then source node reverts back to direct transmission. In such a situation, source node informs destination node and relay nodes with an INFO message.

3.5 ACO Timer Design

As described in previous section, D-CSPA method is based on a distributed architecture. Each relay makes its own decision in a distributed manner. Relays should send their decision of cooperation within an ACO-epoch, when this duration ends, source disseminates data packet. A matter of investigation here is the time that relay nodes send ACO timers. If relay nodes send their ACO timers at the same time then collision occurs in all nodes and either an optimal solution cannot be found or a suboptimal cooperation set is found at the end of ACO-epoch. D-CSPA algorithm needs a timer design to successfully differentiate ACO packets of relays from each other. In this scope, we propose four timer schemes:

1. τ_1 : Predefined timer values
2. τ_2 : Random timer values
3. τ_3 : Timer based on relative power assignment value (ρ)
4. τ_4 : Timer based on relative power assignment value (ρ) and instantaneous channel power (P_{rd})

Best timer scheme is relative and depends on available information about channel statistics.

3.5.1 Predefined timer values

In this timer design, each relay node has a predefined timer value. This implementation eliminates the possibility of ACO collision. Predefined ACO timer values are quite useful if location and average channel statistics of relays are precisely known. This timer design also results in optimal cooperator selection and leads to very effective energy consumption, in such a well-defined environment. However, using this timer may not be feasible if distribution of relay nodes over a geographical area is not predefined and may change randomly during time.

Using such a timer sets a unique order of relays in a cooperation set, but if channel characteristics change by time optimal order of relays also vary for each relay distribution. Consequently, this timer is suitable, where the location and average channel characteristics of nodes are known and optimal order of relays can successfully be calculated beforehand.

3.5.2 Timer based on random values

Relay node may have to determine a timer value in the absence of relative power levels or channel information of cooperative system. We designed this timer for cases with minimum amount of information. In such a lack of information, using this timer design, relay nodes will use random values to set ACO-timers. Each relay node chooses a random value to determine its ACO-timer. Resulting random number corresponds to a random time slot inside ACO-epoch. This timer is quite useful if there is no or less than required information about cooperative system, when deciding on timer value. However, this design brings two problems within: Two relays may choose same or too close random value, which result in ACO-collision. Additionally, a relay that will spend more energy in order to participate in cooperation may be chosen instead of a more energy effective relay. Consequently, using random values for determining ACO-timer, is useful in low information cases, but may lead to random order of relays instead of an energy optimal order in cooperation set.

3.5.3 Timer based on relative power assignment value

In previous section, a timer is designed in the absence of information. More energy effective timers can be used if necessary channel information is provided. An optimal ACO-timer design should be adaptive, and take care of ACO collisions. ACO-timer is mainly used for optimally arranging the order of candidate relays to participate in cooperation. We have two important concerns when designing an ACO-timer:

- Resulting relay order should favor minimal total energy consumption of cooperative system.
- ACO-timer should minimize ACO-collisions.

Our main motivation is to reduce total energy consumption of cooperative system. Total energy consumption of cooperative system is defined in equation (3.8)

It is obvious that total energy consumption of cooperative system is proportional to relative power assignment vector of relay nodes. This leads to the fact that, lower relative power assignment values result in lower total energy consumption. Consequently, relative power assignment value, $\rho_{1,1}$, is selected as the best metric to build an effective ACO-timer. Relay nodes calculate their timers upon receiving C-CTS message, when there is only one node (the relay node making the calculation) in the cooperation set. Hence, each relay determines its ACO-timer based on its average channel conditions only.

So far, $\rho_{1,1}$, is selected as the main metric. We use a template for ACO-timer design, for relay node R_i

$$t_i = a * (\rho_{1,1}(i))^b \tag{3.9}$$

Here, a and b and constants to adjust timer modeling to support optimal timer functionality for all scenarios. As we stated before, ACO-timer design has two main functionalities. We aim to perform these functionalities, and start with defining timer requirements that lead us to reduced energy consumption and reduced number of ACO collisions. Total energy cost of the cooperative system is based on relative power assignment vector. In order to reach minimum total energy cost, relative power assignment values of individual relays in the cooperation set should be kept as low as possible. If we recall definition of relative power assignment value, it is clear that $0 \leq \rho_{1,1} \leq 1$. Relays with low $\rho_{1,1}$ values should transmit their ACO earlier, so timer value should be decreasing as $\rho_{1,1}$ increases. This leads us to the solution that b exponent should be greater than zero.

Secondly, ACO-timer should cause minimum number of ACO packet collisions. In order to solve this problem, we first define ACO packet collision. ACO packet collision is observed in following situtations :

- ACO-timer value is greater than ACO-epoch duration.
- Minimum difference between ACO-timers of relays is greater than MaximumPropagationDelay.

This problem is solved via MATLAB. A meshgrid is formed in MATLAB. The axes of this meshgrid are a and b coefficients of ACO-timer formula. A simulation scenario is formed in MATLAB. D-CSPA model is simulated. Nodes are distributed in horizontal, vertical and square grid topologies. Average channel coefficients are computed for each node. Power assignment value, ρ, is calculated for each (a,b) pair via equation (3.1). ACO-timer is calculated for each (a,b) coefficient pair in meshgrid, using power assignment value in our timer model in equation (3.9). Resulting ACO-timer value is used for determining number of collisions at each (a,b) pair. This simulation is executed for each (a,b) pair in a predefined region. Simulation at each point of meshgrid region, is repeated for different SD distance values. Moreover, at each (a,b) point, same simulation is performed for 1000 times for each SD distance between 10 and 22 m.

These extensive simulations gave 21000 collision levels for each (a,b) pair. An average of these collision levels gave us probability of collision for each (a,b) pair. Contour plot of collision probabilities over predefined meshgrid region, gave us a confidence region of (a,b) pairs, that minimizes collision probability. Finally we selected a coefficient pair from this confidence interval and performed our simulations using that pair.

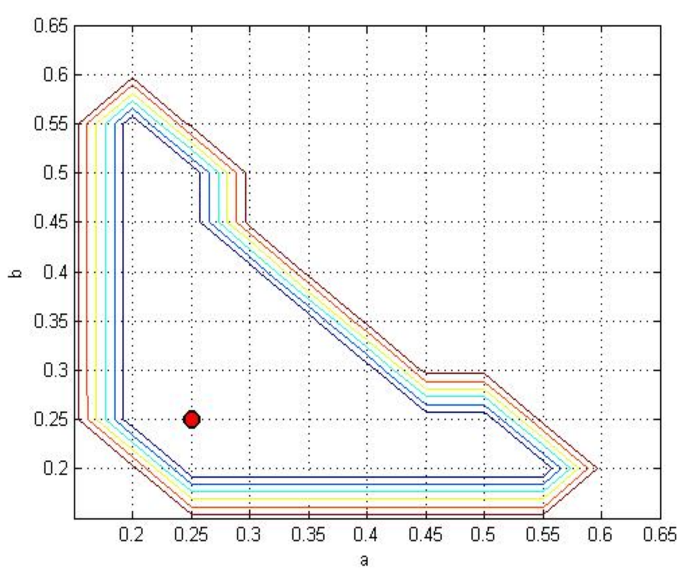

Figure 3.5: Contour plot for probability of collision

In this figure, probability of collision is almost zero inside inside the area surrounded by blue isohips line. Hence we select our timer coefficients inside this region.

We select a=0.25 and b=0.25 , and finalize our timer as

$$t_i = 0.25 * (\rho_{1,1}(i))^{0.25} \tag{3.10}$$

3.5.4 Timer based on relative power assignment value (ρ) and instantaneous channel power (P_{rd})

In previous section, we defined a new intelligent ACO-timer, based on relative power assignment value of the relay. This timer design favors the relays with lower relative power assignment values to join the cooperation set earlier. As a result, lower energy consuming relays exist in cooperation set and hence total energy consumption of the system is decreased. This model works fine for selecting relays, however one of the main requirements of an ACO-timer is to differentiate between candidate relays. This timer is based on average channel values like SD link average SNR, SR link average SNR, RD link average SNR. A formulation based on average channel statistics will result in same values for relay nodes that are in symmetrical position with respect to both source and destination at the same time. Average channel statistics are proportional to distance, and if SR and RD distances are same for two relays, then their ACO-timer will also be same. Transmission of two ACO packets from different relay nodes at the same time will certainly result in collision at receiving source, relay and destination nodes, which means that ACO-packets will not be analyzed properly, optimal cooperation set will not be found and a disinformation will occur between source and relay nodes.

In order to overcome this problem, a new timer design is proposed. A new metric should be added to existing timer scheme. This new metric should be in compliancy with the intelligence of the current timer. Under these constraints, we decided to use instantaneous RD link power level as this new metric. Instantaneous RD link power level is different for each relay node, because of Rayleigh fading. However, this new metric should be added in an intelligent manner, to facilitate cooperations and end up with an optimal cooperation set. We define our constraints here:

- This new part of the timer should favor the relay with better instantaneous RD channel power level.

Under these constraints, this new timer is found to be inversely proportional with P_{rd}, so that if P_{rd} is high then ACO-timer value should be low. We use a template for ACO-timer design:

$$t_i = c * (\frac{P_{rd}(i)}{P_{sd}})^{-d} \tag{3.11}$$

Here, c and d and constants to adjust timer modeling to support optimal timer functionality for all scenarios. P_{sd} is SD channel power, used for normalizing timer value. P_{sd} is same for all relay nodes and has no effect on relative timer values of relay nodes. The aim of this timer is to eliminate collision. We start timer modeling with defining collision: Two ACO packets collide, if related ACO-timers expire within same interval. Here we define that interval as maximum propagation delay. If difference between ACO-timers of two or more relays is below a certain threshold, which is maximum propagation delay here, collision can happen.

This problem is solved via extensive simulations in MATLAB. A meshgrid is formed in MATLAB, using range of values for c and d coefficients of timer. Each (c,d) pair corresponds to a specific ACO-timer value. D-CSPA system is simulated in MATLAB as described in previous timer design. MATLAB simulations are used to find number of ACO collisions for each case.

At this point, designed timer is checked against another constraint :

- This new part of the timer should not change the order of relays determined by existing timer based on relative power assignment value.

If new timer changes the order of relay nodes for a (c,d) pair, we assumed that this pair of coefficients cause collision.

These simulations gave 21000 results for each (c,d) pair. Number of ACO collisions at each point is calculated and results are depicted in following figure : We select our

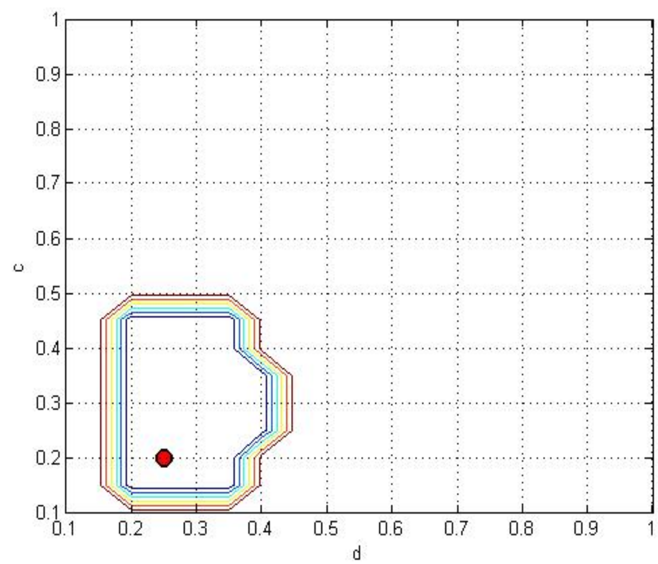

Figure 3.6: Contour plot for probability of collision

coefficients from this graph, as c=0.2 and d=0.25 .

Finally two timer schemes are combined to form new timer, for relay node R_i:

$$t_i = 0.25 * (\rho_{1,1}(i))^{0.25} + 0.2 * (\frac{P_{rd}(i)}{P_{sd}})^{-0.25} \tag{3.12}$$

This new timer selects relays with low power consumption and high RD channel quality. Consequently, if instantaneous channel information is also present in addition to relative power assignment values, an energy efficient timer design which also minimizes collision probability can be obtained.

3.6 Collision Resolution

Source uses ACO-epoch in order to collect cooperation requests of relay nodes. After a successful ACO-epoch, a cooperation set is formed.

When candidate relay nodes send their ACO packets, successfully designed ACO timer algorithm should generate ACO timer values that should avoid collision. However, still there is the chance to have collision of ACO packets. In such a case, normal D-CSPA algorithm would end cooperative transmission and revert back to direct transmission which would most probably result in failure. Such a failed data transmission would rise a retransmission which makes the successful transmission costly in terms of energy spent and time consuming. In order to overcome this problem, we propose a modification on COMAC protocol, by introducing second ACO-epoch to the system. In existing COMAC protocol, at the end of ACO-epoch, if an optimal cooperation set is not found, source node cancels cooperative transmission by sending an INFO packet, and reverts back to direct transmission.

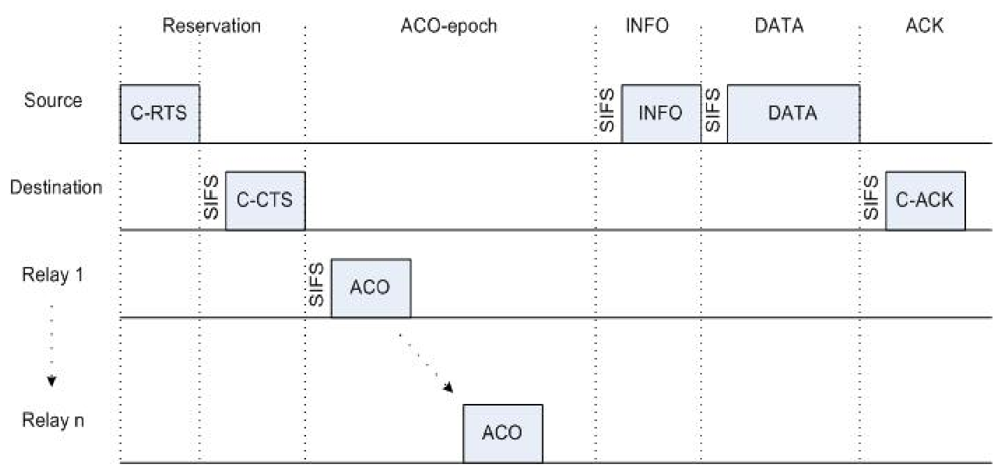

Figure 3.7: Frame exchange when cooperation initiation is not successful

Here we propose a modification to COMAC protocol in order to provide ACO collision resolution and overcome ACO collision problem. In our proposed model, when ACO-epoch ends, source node determines an estimate for received power at destination, based on existing average channel statistics and relative power assignment values in ACO packets. Using this estimation, source node decides whether existing cooperation set is successful or not, based on SNR requirements. If source node senses an ACO collision and existing cooperation set is not satisfactory, in other words when source node decides that optimal cooperation set is not found in first ACO-epoch ACO_I, then it starts second ACO-epoch ACO_{II}. In second ACO-epoch, relay nodes recalculate their ACO timers and ACO-epoch follows as described in previous section. It is obvious that if relay nodes use same metrics and same formulas to calculate ACO-timers, same ACO packet collision would be observed during ACO_{II}. This argument proves that we need a different metric to calculate ACO-timer values in the second phase. In order to successfully differentiate ACO timers in the second ACO-epoch, we use instantaneous RD link power levels. This information is different for each relay. However, if this information is not available, then relay node assigns a new timer based on random values. In such a case, relay node determines a timer value based on random number generation and resulting ACO-timer is added to previous timer value. Hence, new timer is the sum of the ACO-timers defined in ACO_I and ACO_{II}.

As described above, if an optimal cooperation set cannot be found in ACO_I, relay and destination nodes are informed by source node via INFO message. Upon receiving INFO message, relay and destination nodes understand that first ACO phase is not successful and second ACO phase will start, and update their NAV timers accordingly. If second ACO phase results in an optimal cooperation set, source node ends ACO_{II} and sends data signal. If second ACO phase also results in a suboptimal cooperation set, source node reverts back to direct transmission.

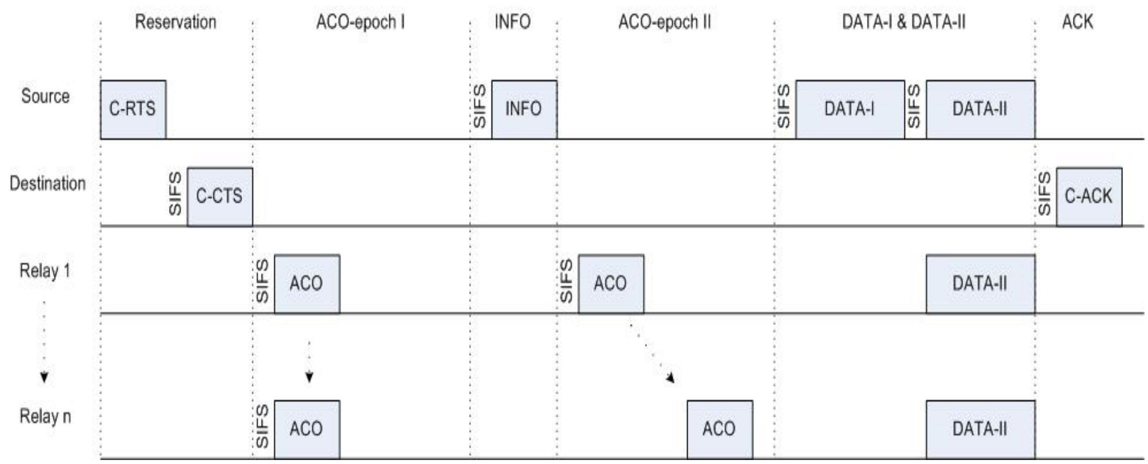

Figure 3.8: Frame exchange with ACO collision resolution

Flowchart at source node and relay nodes is give in Figure 3.9 and 3.10:

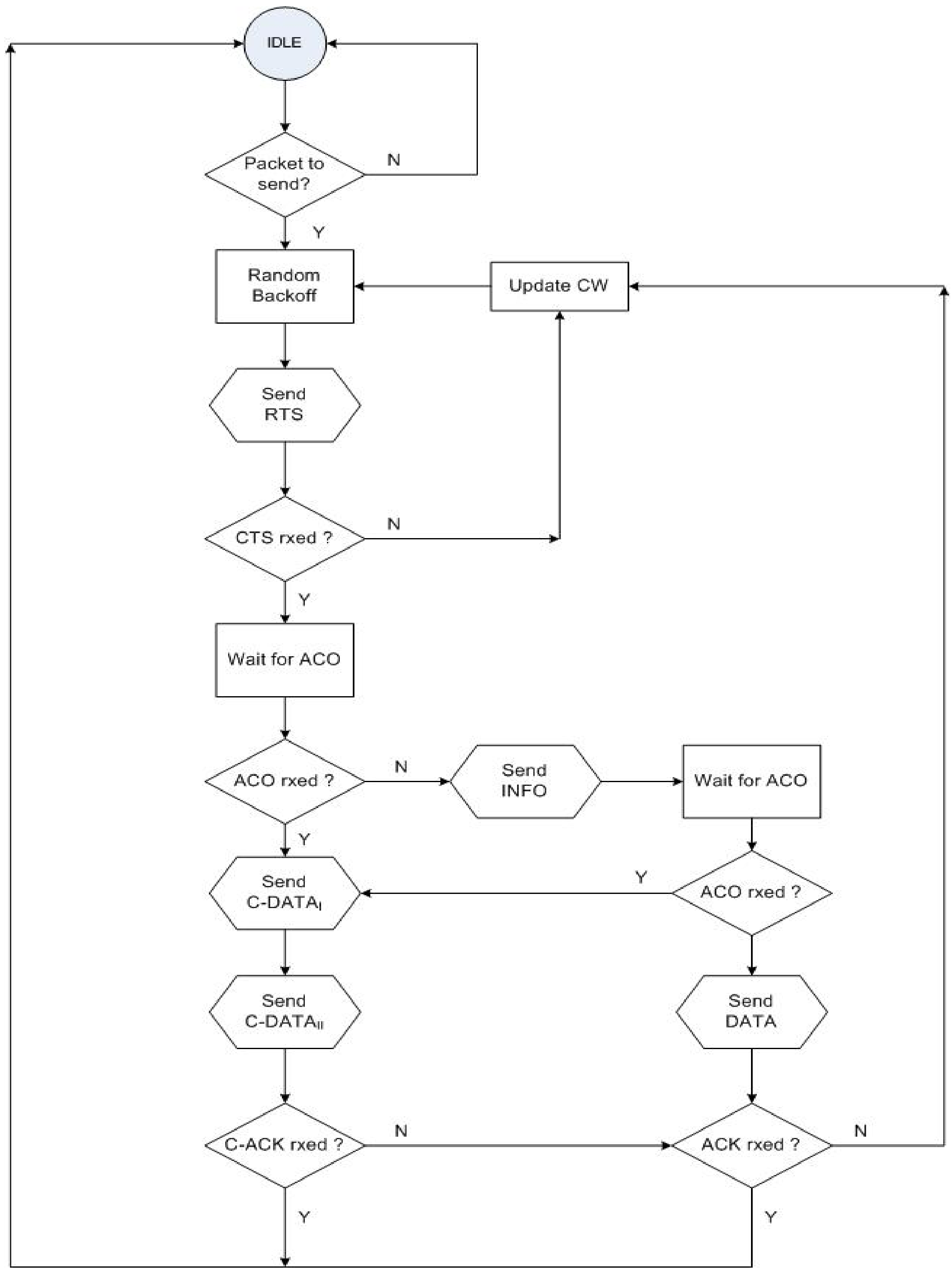

Figure 3.9: Flowchart at the source node

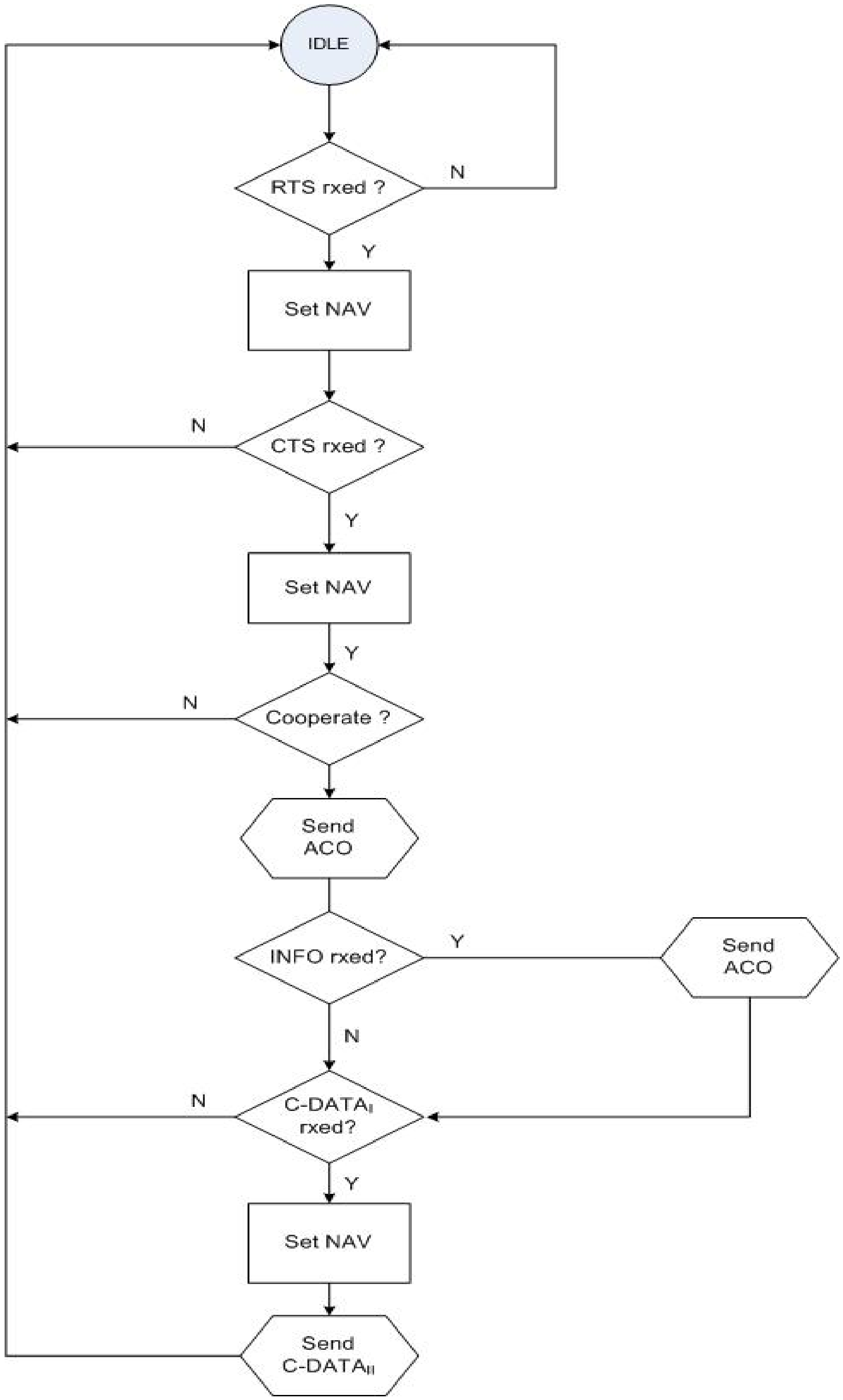

Figure 3.10: Flowchart at relay nodes

3.7 Cooperation Mode

Multiple access schemes are used to allow many mobile users to share simultaneously a finite amount of radio spectrum. The sharing of spectrum is required to achieve high capacity by simultaneously allocating the available bandwidth (or the available amount of channels) to multiple users. CDMA and TDMA are among major multiple access techniques used to share available bandwidth.

During second data phase of cooperative transmission, source node and relay nodes repeat the data signal together. All nodes in the cooperative system, try to access the medium during this period. We implemented two multiple access schemes CDMA and TDMA, for source and relay nodes to access medium in COMAC protocol second data phase.

3.7.1 CDMA

Code division multiple access (CDMA) is a channel access method used by various radio communication technologies. Multiple access techniques used in wireless networking, either divide the existing channel into frequency bands or allocate the channel in bursts. However, in CDMA each station transmits over the entire frequency spectrum all the time [52]. CDMA uses spread spectrum technology and a special coding scheme (where each transmitter is assigned a code) to allow multiple users to be multiplexed over the same physical channel. Each user in a CDMA system uses a different code to modulate their signal. CDMA allows users to transmit their signals at the same time [47]. When we use CDMA in COMAC $DATA_{II}$ phase, each node sends its data signal copy at the same time.

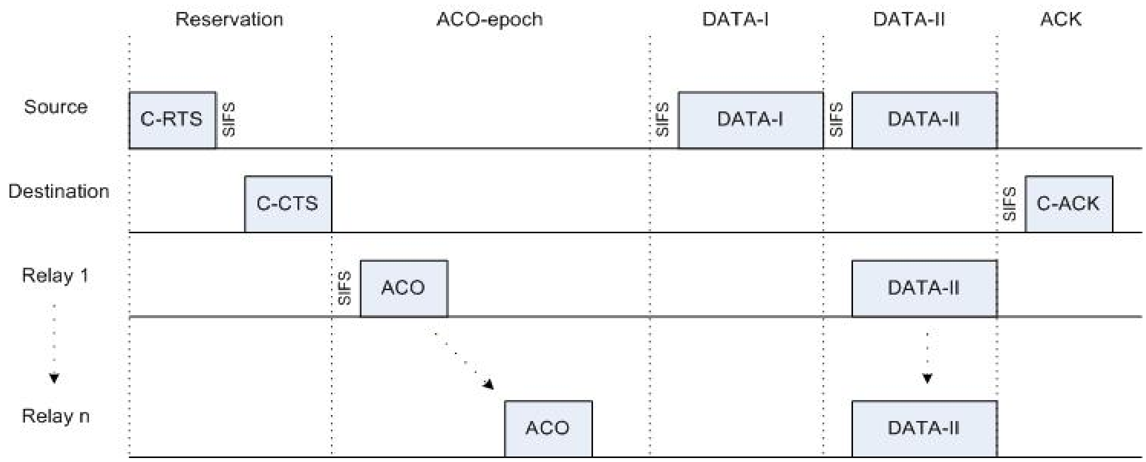

Figure 3.11: Frame exchange for CDMA

3.7.2 TDMA

TDMA is a channel access method for shared medium networks. TDMA systems divide the radio spectrum into time slots and in each time slot only one user is allowed to either transmit or receive [47]. Time division multiple access (TDMA) is a channel access method for shared medium networks. It allows several users to share the same frequency channel by dividing the signal into different time slots. The users transmit in rapid succession, one after the other, each using its own time slot. This allows multiple stations to share the same transmission medium (e.g. radio frequency channel) while using only a part of its channel capacity. TDMA is used in the digital 2G cellular systems such as Global System for Mobile Communications (GSM), IS-136, Personal Digital Cellular (PDC), and in the Digital Enhanced Cordless Telecommunications (DECT) standard for portable phones. When we use TDMA in COMAC second data phase, each node sends its data signal in a separate time slot. The order of cooperation announcement also defines the order of data sending in phase 2. This multiple access method, increases total transmission time, which causes a decrease in throughput.

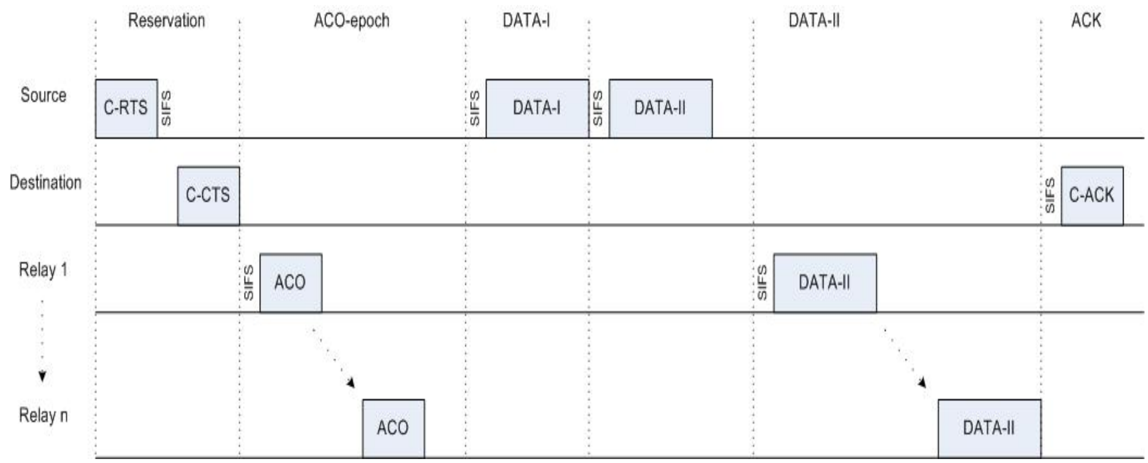

Figure 3.12: Frame exchange for TDMA

3.8 Sleep Feature

Sensor networks are battery powered devices. Energy efficiency is one of the main concerns for sensor nodes. When a sensor node is placed in a location, it remains there until its battery is exhausted. It is not likely to change batteries of such sensor nodes. Implemented MAC protocol should take care of energy efficiency in order to provide better battery life. MAC protocol should avoid unnecessary energy consumptions. In general, radios operate in four different modes: Idle, Receive, Transmit, and Sleep. While it is expected that the radio consumes the most energy in the "Transmit" and "Receive" modes, running in the "Idle" mode is also costly. In most cases, operating in "Idle" mode results in significantly high energy consumption, because the radio electronics have be turned on and continually decode radio signals, even noise, to detect the presence of an incoming packets. Different measurements have shown that the energy consumption ratio of these three modes could be as 1:1.05:1.4, 1:1:2.7, and 1:2:2.5, respectively [53]. It is thus desirable to completely shut down the radio rather than transiting into the "Idle" mode. However, switching a radio on and off very frequently can sometimes result in even more energy consumption than leaving the transceiver unit in "Idle" mode because of the start-up power. Moreover, as the transmission packet size gets smaller, the transition energy becomes dominant to the energy consumed during receiving and transmitting of packets. Therefore, it is important to take this issue into account when designing energy-efficient MAC protocols.

Major sources of energy waste is listed as follows:

- Collision
- Overhearing
- Control packet overhead

- Idle listening

Collision

In previous section, we proposed a modification to existing COMAC protocol that provides ACO collision resolution. A new timer is designed to differentiate the candidate relays. Also a new ACO-epoch is introduced to the protocol, which is used in case of ACO collision. These two solutions address collision problem.

Overhearing

Overhearing means that, nodes receive messages that are destined to other nodes. In our protocol, during ACO-epoch, relays that will not participate in cooperation hear ACO packets unnecessarily. In addition, overhearing occurs for data packets also. The relay nodes that do not cooperate overhear the data packets.

Idle Listening

Relays stay in idle state even when they are not receiving a packet, in order to sense the medium and receive possible incoming packets. However, energy consumption continues when relay is idle state. During ACO-epoch and also data phase, a relay node, that decided not to cooperate, does not need to receive and incoming packets, and hence such a relay node does not need to stay in idle state in order to sense medium.

As stated above, collision problem is successfully solved with the new timer design and COMAC protocol modification to support collision resolution. Here we introduce a new model, called as sleep model, as a further modification to COMAC protocol. In this model, relay nodes that decides not to cooperate, go to sleep state during data transmission, and wake up when cooperative transmission ends. In existing model, relay nodes decide whether they will cooperate or not when they receive C-CTS or when they receive ACO during ACO-epoch. If a relay node concludes that it will not cooperate, then it sets its NAV timer for the rest of the transmission, and goes to idle state. Idle mode is less power consuming then sending and receiving, however, a node in idle state still hears the packets in the medium, and spends energy for staying in idle state and receiving packets in the medium that are not destined to itself. In our sleep model, relay nodes that will not cooperate, set their NAV timers as described in COMAC protocol and go to sleep state. During this sleep period, energy consumption of relay node is minimized. Moreover, relay nodes do not hear and/or receive any packets during sleep period, which is also another important point for energy saving. Implementation of this sleep model requires sensitive adjustment of NAV timers. If NAV timers are not well designed, undesired results may occur. If a node stays in sleep state before transmission ends, then there will be unnecessary energy consumption for remaining time. If a node stays in sleep state after transmission ends, then there is the risk that this node cannot receive C-RTS, C-CTS messages of next transmission. Here we revisit NAV timers of relays in COMAC protocol.

Relay nodes should set their NAV timers based on existence of cooperative transmission or not. Each node makes this decision and go to sleep state at three instances:

- Upon receiving CTS
- Upon receiving ACO
- Upon receiving INFO

Upon receiving CTS, a relay node has two important information: The scheme of transmission, direct or cooperative. This information is extracted from CTS message. The second important information is, whether this relay is a candidate relay or not. Based on channel characteristics gathered from RTS and CTS, relay node executes cooperation decision function and concludes whether to cooperate or not. At this point, if relay node ends up with coperative transmission but it cannot be a candidate relay, then this relay should set NAV timer and do not access medium till the end of

ACO-epoch. During this NAV period, this relay node has nothing to do than waiting in idle mode. Hence, we configured the relay node to go to sleep state at this instance in order not to receive any ACO packets during ACO-epoch. NAV timer expires at the end of ACO-epoch, since it is not certain yet, whether direct or cooperative transmission will be used. A new NAV timer will be set depending on the decision of source node about the type of transmission. If a relay node receives an ACO packet, then it is a candidate relay. However, there is another relay in the medium that has a shorter waiting time, and has sent its ACO earlier. When a candidate relay node receives such an ACO packet, executes cooperation decision function based on the information delivered via ACO packet. If decision function indicates that this relay is no longer a candidate relay, then relay node should set its NAV timer and do not access the medium till the end of ACO-epoch. Here, we configured this node to sleep during this period, in order not to receive further ACO packets. The third point of decision for sleeping is the end of ACO-epoch. At this point, type of transmission, direct or cooperative, becomes certain. Sleeping nodes wake up at this point and start to receive next packet. In case of direct transmission, next packet is an INFO packet. The relay nodes check the type of packet from the header of incoming packet and immediately go to sleep state if packet type is INFO, indicating direct transmission. In this case, NAV timer is set as the duration of a data packet and an acknowledment packet. If type of packet is DATA, and if the relay node does not exist in the final cooperation set, then this relay node goes to sleep state, configuring its NAV timer according to cooperative transmission. This NAV timer equals to twice the duration of data packet plus the duration of acknowledgement packet. Additional inter frame spacings and propagation delays are included at each NAV timer by default.

Following Figure 3.14, illustrates radio states for a relay node that does not participate in cooperation. In this scenario, relay node receives C-RTS and C-CTS, and

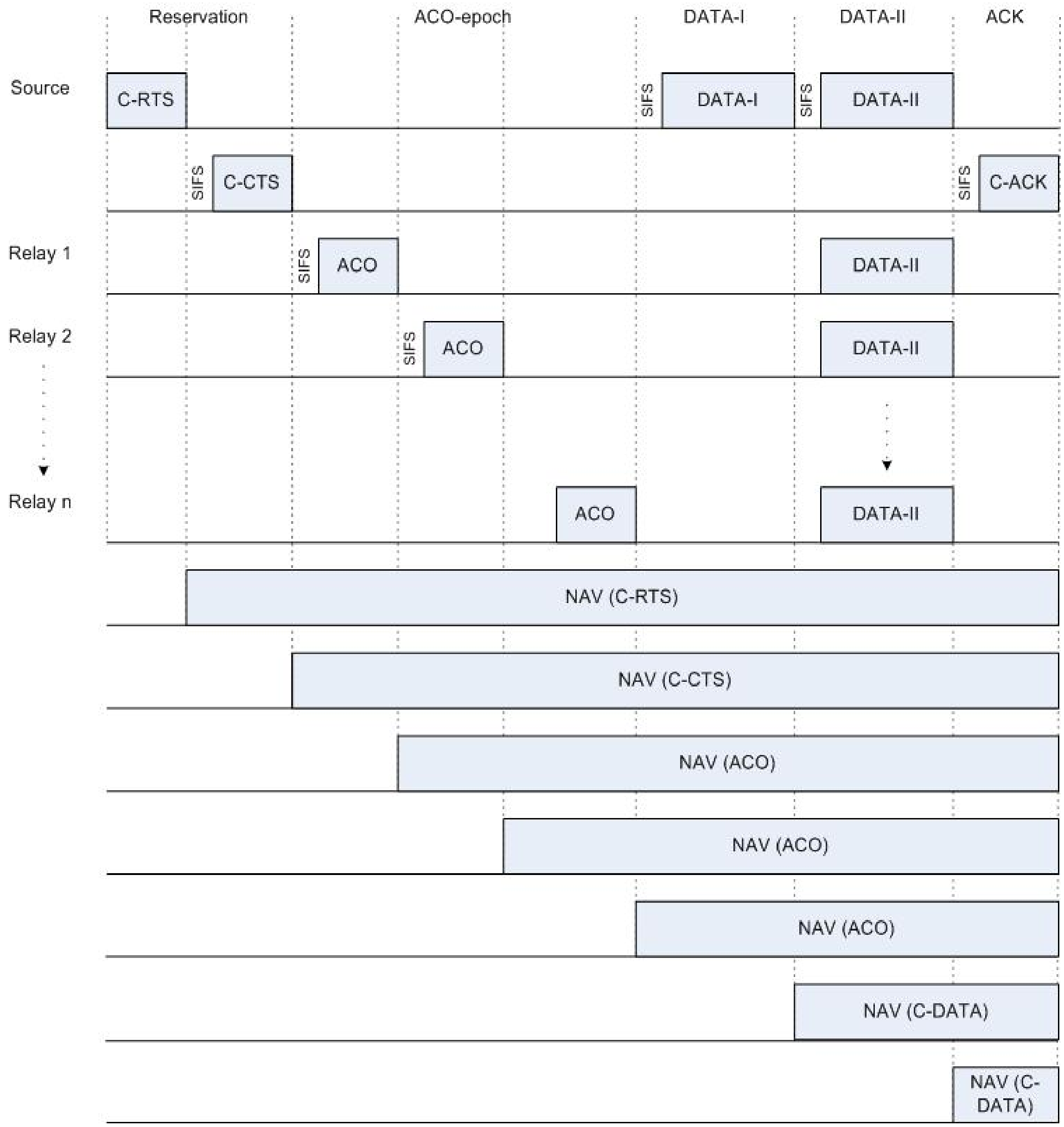

Figure 3.13: Frame exchange and NAV settings for D-CSPA

decides not to cooperate when it receives ACO message from another relay node.

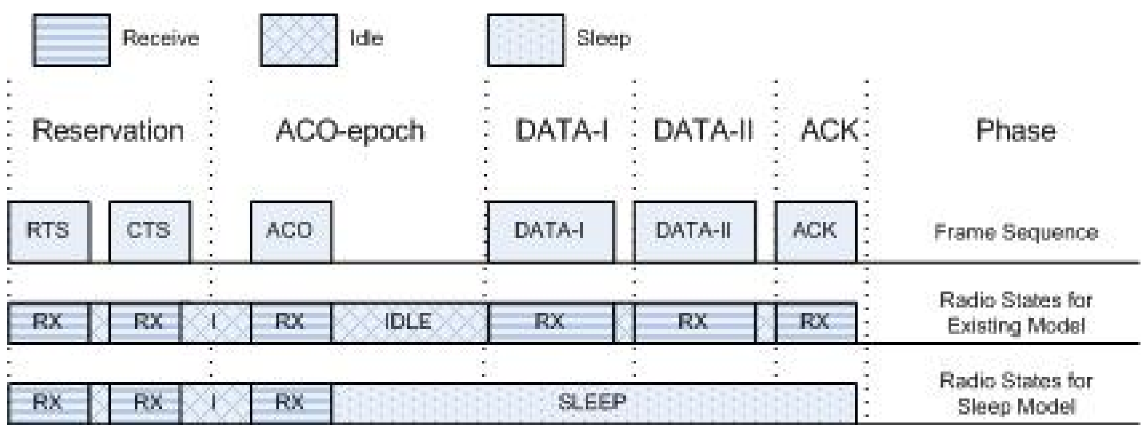

Figure 3.14: Radio states with sleep model

4 PERFORMANCE ANALYSIS

4.1 Simulation environment

NS-2 (Network Simulator version 2) is an object-oriented, discrete-event-driven network simulator targeted at networking research, which has been extensively used by the networking research community [50]. Ns2 can be built on unix based operating systems like Linux, however there are also means to utilize ns2 under Microsoft Windows. VMWare Player can be used to simulate a Unix based environment under Microsoft Windows. Another way to build ns2 under Windows is Cygwin which provides a Linux like environment under Windows. Ns2 is open source and widely used, which allows users fully control over the platform and perform necessary modifications on protocols. As a result of this open source structure, users can develop own protocols and applications. COMAC is a modification of MAC 802.11 protocol, and ns2 is a suitable tool for implementing necessary modifications on original MAC 802.11 in order to end up with a realtime COMAC protocol simulation. Two programming languages are used for scripting in ns2. Main simulation environment is created using C++. Layers of all communication protocols, MAC, PHY layers and also routing layers and application layers are written in C++. Additionally, another frontend scripting language, OTCL is used for creating simulation scenarios, passing variables to simulations, manipulating C++ parameters or extracting info from realtime simulation via triggered events. OTCL is also used to describe topology of the network and specify protocol specific parameters. We used ns2.30 and cygwin 1.5.1 during simulations.

4.2 Simulation model

In order to implement COMAC with D-CSPA in ns2, we modified MAC layer PHY layer code of original protocol. MAC Layer MAC layer of the protocol is handled by mac-802_11.cc and mac-802_11.h files. New MAC packets, ACO and $DATA_{II}$ are introduced to the protocol here. Multiple access scenarios are implemented in this layer. PHY Layer PHY layer of the protocol is handled by wireless-phy.cc and wireless-phy.h files. This layer handles sending packets that come from upper layers to the medium and also handles receiving packets that come from physical medium and passes these packets to upper layers after performing necessary inspections.

The packets are generated according to Poisson distribution at an average rate of 125 kbps. Data transmission is done at 250 kbps. Data packet size is 128 bytes. C-RTS packet is 16 bytes, C-CTS packet is 14 bytes, ACO packet is 14 bytes and ACK packet is 14 bytes. Maximum transmission power is set as 1mW, according to Chipcon CC2420 datasheet.

Two-ray ground model is used as a radio propagation model [47]. Two-ray ground path loss model with exponent 4 is implemented.

The channel is assumed to be a Rayleigh fading channel. Fading is applied to data packets and each data packet is assumed to undergo independent Rayleigh fading.

At the receiver, a packet is accepted as successful if its instantaneous SNR is 20 dB above the receive threshold.

4.3 Performance results

In this section, we provide results of simulations of COMAC with D-CSPA. Effect of cooperator selection model results are analyzed first with following scenarios :

- MAC 802.11 with direct transmission

dataRate	0.25 Mb
basicRate	0.25 Mb
CWMin	7
CWMax	31
SlotTime	320 μsec
SIFS	192 μsec
PreambleLength	32
PLCPHeaderLength	12
PLCPDataRate	0.25 Mb
RTSThreshold	0
ShortRetryLimit	7
LongRetryLimit	4

Table 4.1: Simulation Parameters

- COMAC with D-CSPA
- COMAC with O-CS and R-CS

Next, effect of timer design is analyzed for following timers :

- Timer based on predefined values : τ_1
- Timer based on random values : τ_2
- Timer based on relative power assignment values : τ_3
- Timer based on relative power assignment value (ρ) and instantaneous RD link power levels (P_{rd}) : τ_4

These timer may be called with their respective symbols (τ_1,τ_2,τ_3,τ_4) in the rest of the chapter.

Then, effect of cooperation mode is analyzed for following multiple access schemes:

- CDMA
- TDMA

Finally, performance of sleep model is analyzed in following scenarios:

- Direct transmission
- COMAC with D-CSPA without sleep model
- COMAC with D-CSPA with sleep model

Simulations are carried out for following topologies :

Horizontal Topology

In this topology, nodes are aligned on the axis that is connecting source node and destination node. Half of the nodes are between source node and destination node, where remaining half of the nodes are on the other side of source. This kind of node deployment can be encountered in pipeline or border surveillance applications, where nodes are communicating with another node on the path to the base station [41].

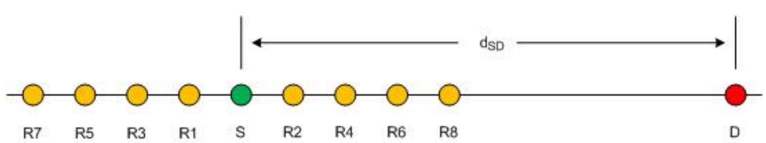

Figure 4.1: Horizontal Topology

Vertical Topology

Relay nodes lie on a line that is perpendicular to the line connecting source node and destination node. Nodes are symmetrically distributed on both sides of source node as shown in figure. This kind of node deployment can be seen in pipeline, bridge monitoring and border surveillance applications [41].

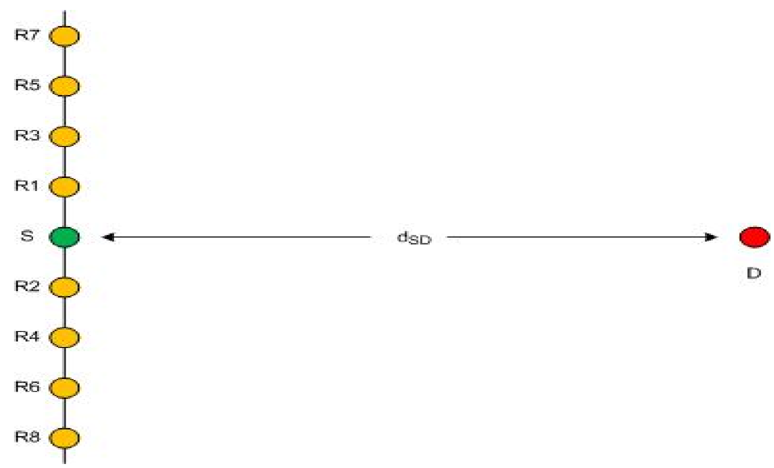

Figure 4.2: Vertical Topology

Square Grid Topology

In square grid topology, nodes are located in a 3x3 grid. Source node is in the center of the grid, and relay nodes are on the centers of each 1x1 square as shown in the figure. This kind of node deployment can be seen in habitat monitoring applications [41].

Random topology

In this topology, nodes are randomly distributed in the region. In our simulations, we distributed 8 nodes randomly in a 3x3 square, where source node is in the center of the square. A sample random distribution is illustrated in following figure. 20 simulations are performed and results are averaged. This kind of deployment can be seen in surveillance applications in hostile environments [41].

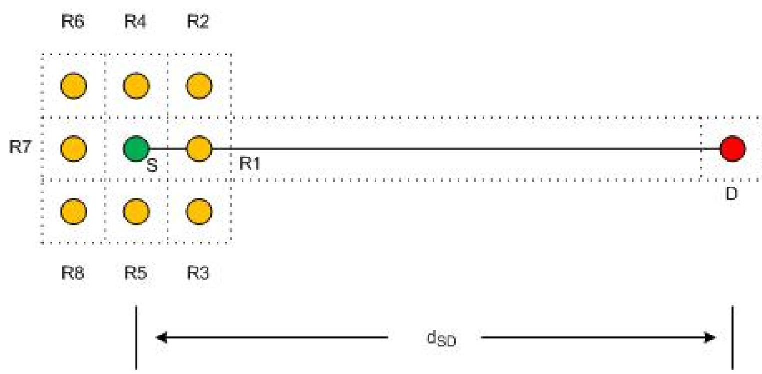

Figure 4.3: Square Grid Topology

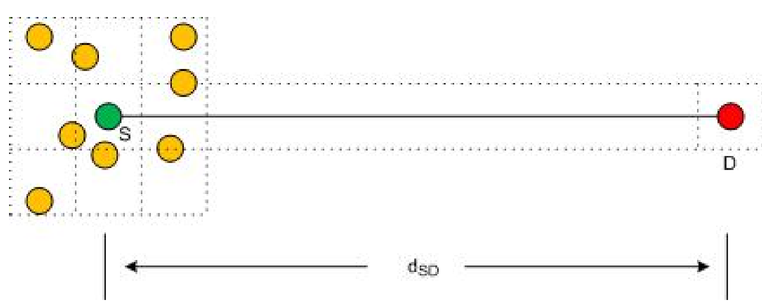

Figure 4.4: Random Topology

4.3.1 Effect of cooperator selection model

Energy-per-bit performance

First we analyze the effect of cooperator selection model.

D-CSPA selects cooperators in a distributed manner, and assigns power levels dynamically as described in previous chapter. R-CS selects cooperators randomly among the neighbours. R-CS uses fixed power levels, which equals to maximum available transmission power. O-CS has a centralized architecture. Cooperating relays are selected by a central node which has all information about the channel conditions of all nodes in the cooperating system. O-CS also uses fixed power levels, which equals to maximum available transmission power.

When square grid deployment is used, D-CSPA algorithm gives us best results in terms of energy-per-bit. O-CS algorithm also selects best relays, however does not assign optimal power levels to these relays, and for this reason energy-per-bit performance of O-CS is worse than D-CSPA. R-CS is the worst method here, due to random cooperator selection and fixed power assignment. In Figure 4.5, sudden changes at certain points indicate an increase at number of cooperators.

D-CSPA is the most cost effective solution in terms of energy-per-bit among different cooperator selection algorithms. In addition, when we check energy-per-bit performance of direct transmission in Figure 4.6, it is seen that cost of direct transmission is 100 times higher than the cost of D-CSPA.

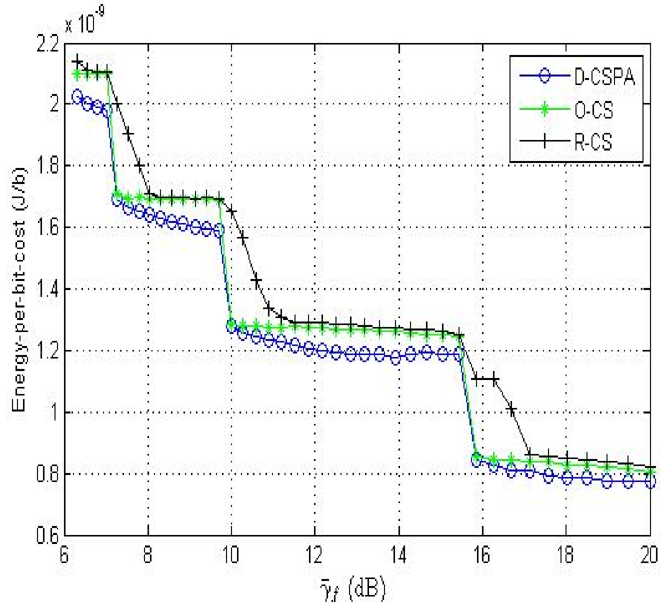

Figure 4.5: Energy-per-bit-cost of cooperative transmission for square grid topology

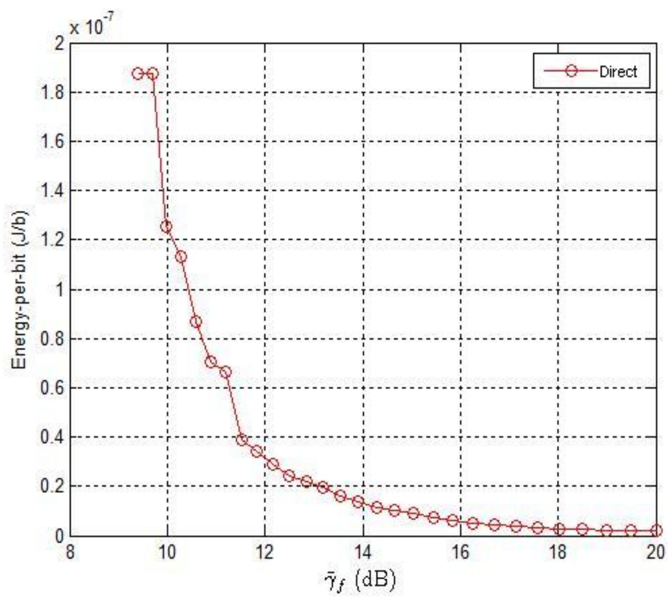

Figure 4.6: Energy-per-bit-cost of direct transmission for square grid topology

In the following Figure 4.7, energy-per-bit performance of cooperation models are depicted. This time nodes are distributed randomly in a 3x3 area. 20 simulations carried out and results are averaged at the end of 20 simulations. This figure has the similar results as in square grid topology, which proves that D-CSPA gives better results than O-CS and R-CS, and outperforms direct transmission significantly in terms of energy-per-bit.

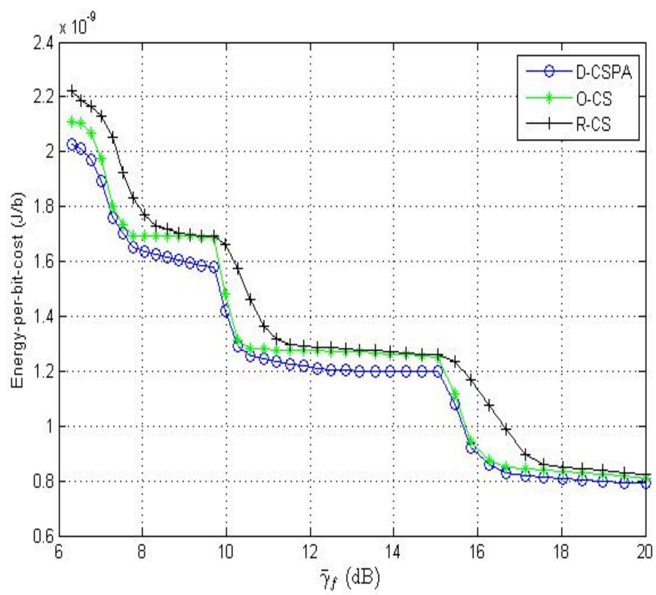

Figure 4.7: Energy-per-bit-cost of cooperative transmission for random topology

Energy-per-bit performances of horizontal and vertical topologies are depicted in following Figures 4.8 and 4.9 respectively. D-CSPA algorithm gives better results in both topologies than O-CS algorithm. Random cooperator selection algorithm, R-CS, has higher energy-per-bit values in both topologies.

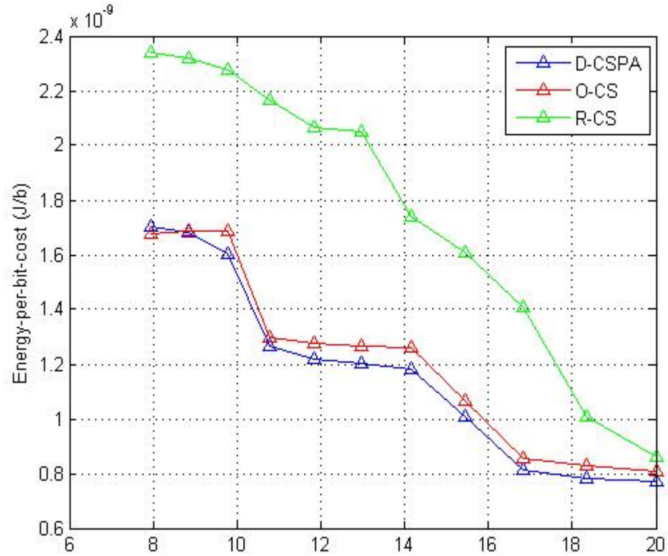

Figure 4.8: Energy-per-bit-cost of cooperative transmission for horizontal topology

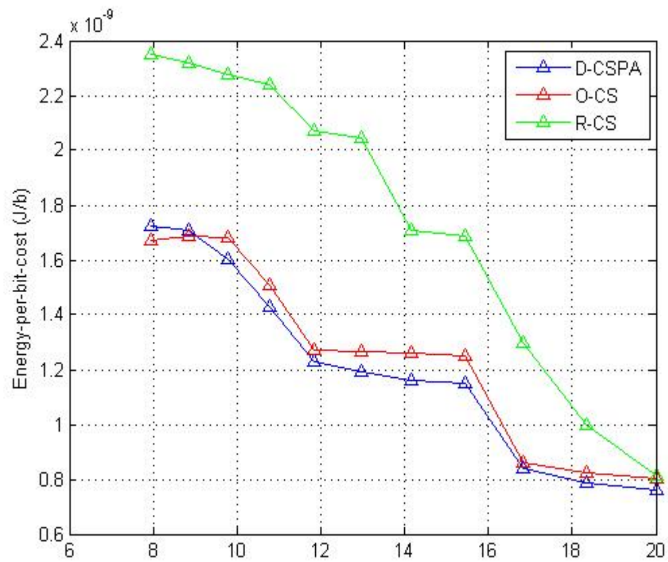

Figure 4.9: Energy-per-bit-cost of cooperative transmission for vertical topology

Average Delay performance

Next we analyze average delay performance. Average delay is measured per successful packet, in source node, as the time difference between the packet generation time and time of acknowledgement message. As seen in Figure 4.10 , cooperation models D-CSPA, O-CS and R-CS have similar average delays. Average delay is calculated per successful packet. Figure 4.11 indicates that successful packet amount is quite low in direct transmission and the results indicate that, average delay of direct transmission is up to 250000 times higher than cooperative transmission, depending on the average SD power level.

When we check the average delay results in random topology in the Figure 4.12, it is shown that average delay performance of the cooperative system is better than that of direct transmission.

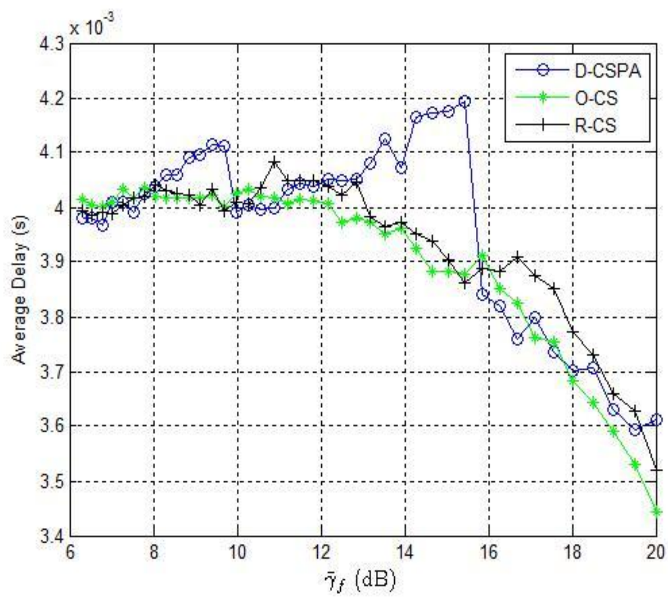

Figure 4.10: Average delay of cooperative transmission for square grid topology

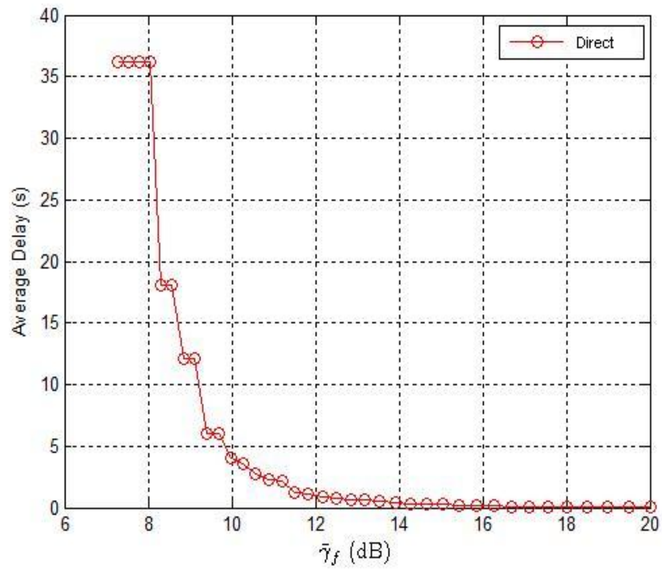

Figure 4.11: Average delay of direct transmission for square grid topology

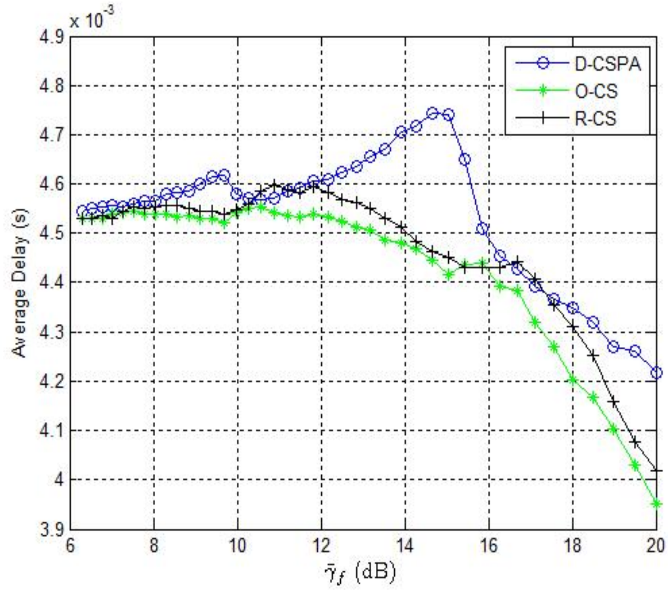

Figure 4.12: Average delay of cooperative transmission for random topology

MAC overhead bandwidth performance

Cooperative system increases number of control packets sent for successfully transmitting one data bit. We measure this MAC overhead bandwidth by accumulating all control packets during simulation time and finally dividing by number of successfully transmitted packets and time. MAC overhead includes all control packets with additional fields for channel state information. As we see in Figure 4.13, MAC overhead bandwidth is almost same for all cooperation models. Bandwidth cost of the cooperative system increases as number of cooperators increase. Direct transmission has lower number of control packets by its nature, however, Figure 4.14 indicates that lower number of successful transmissions increase the MAC overhead bandwidth cost of the direct scheme. Next, MAC overhead bandwidth is checked for random node deployment. Cooperative system consumes very low bandwidth when compared with direct transmission, as shown in Figure 4.15.

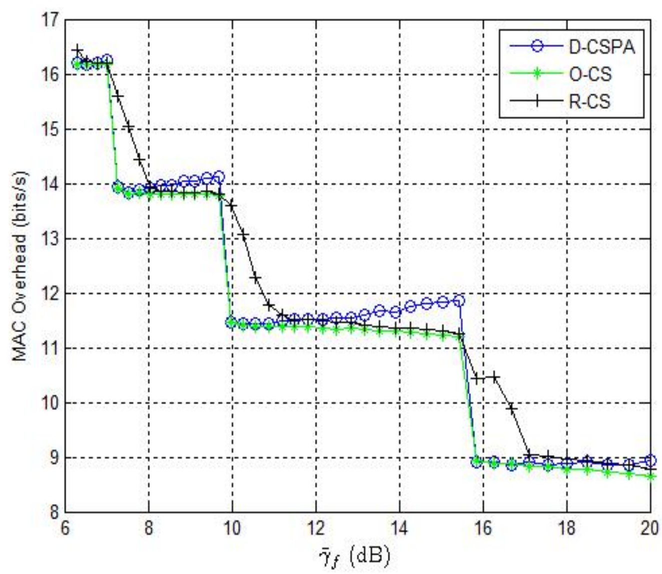

Figure 4.13: MAC overhead bandwidth of cooperative transmission for square grid topology

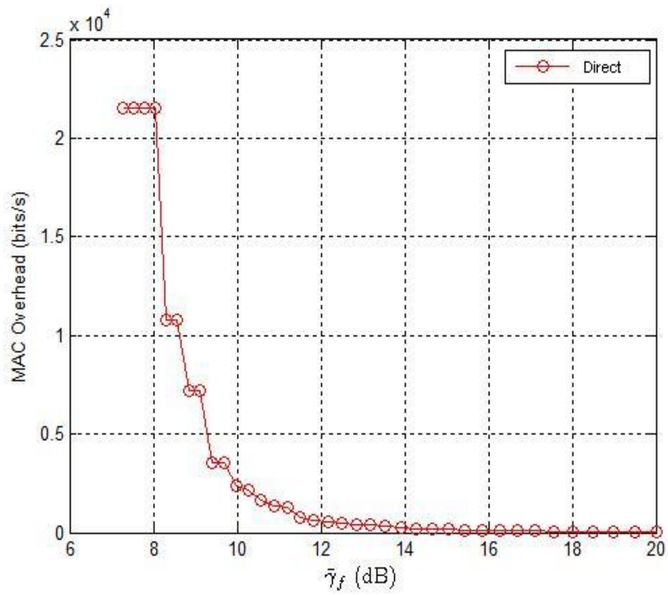

Figure 4.14: MAC overhead bandwidth of direct transmission for square grid topology

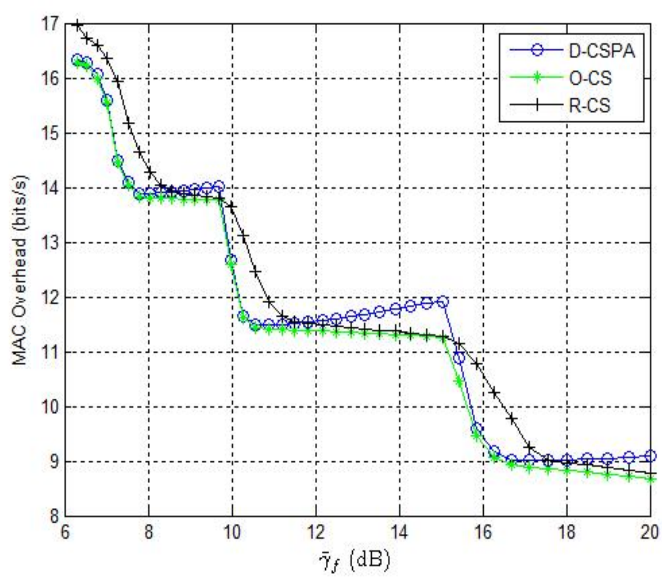

Figure 4.15: MAC overhead bandwidth of cooperative transmission for random topology

Throughput performance

Finally, effect of cooperative transmission on throughput is analyzed. Total successfully transmitted number of bits is divided by simulation time It is clear from Figure 4.16 that throughput of cooperative system performs far better than direct system. Throughput of the cooperative system is around 65000 bits per second for D-CSPA, O-CS and R-CS, where throughput of direct transmission is close to 13000 for low SD distance, and decreases to zero as SD separation is increased.

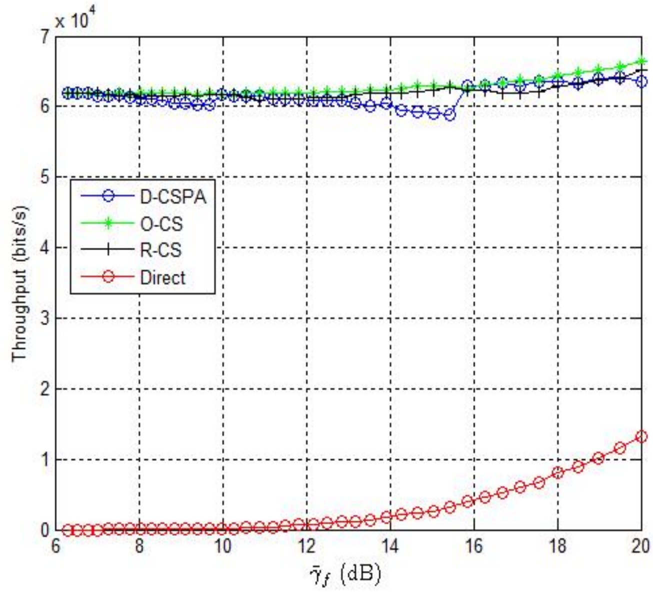

Figure 4.16: Throughput of cooperative transmission for square grid topology

Throughput performance of cooperative system is proven in Figure 4.17 for random node deployment also:

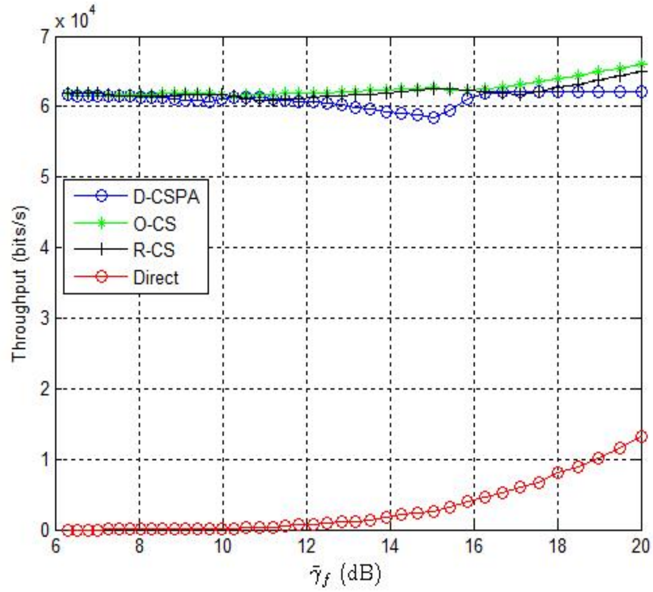

Figure 4.17: MAC overhead bandwidth of cooperative transmission for random topology

4.3.2 Effect of ACO timer design

ACO packets should be sent by relays nodes in correct sequence in order to optimal cooperation set. According to our protocol, whenever a relay node sends an ACO packet, it updates the cooperation set by adding itself into the cooperation set. However existing relays in the cooperation set are never removed. Hence, once a node sends ACO, other relay nodes make necessary computations according to existing cooperation set. For this reason, relay nodes should announce their cooperation decision in correct order. ACO timer defines ACO packet sending time of a relay node. Timer design should be handled carefully to end up with proper ACO order, and an optimal cooperation set. We analyze four different ACO timers, in this work. For each timer, we analyze throughput performance, and also number of ACO collisions observed at source node for three topologies, considering timers $\tau_1, \tau_2, \tau_3 and \tau_4$:

First we look at square grid topology results, in terms of throughput in Figure 4.18

In square grid topology, predefined timer and timer based on relative power assignment value and instantaneous RD channel power give best results. Timer based on relative power assignment only has a throughput close to 60000. 4∼5 % percent decrease in throughput is due to collisions. When a timer based on random values is used in square grid topology, throughput decreases to 50000. Increased probability of collision causes a 15% decrease in throughput, as expected. Number of collisions observed at source node is also a measure of performance. First we look at square grid topology results, in Figure 4.19.

In square grid topology, timer based on relative power assignment value and instantaneous RD channel power indicates no collision at source node. However, when timer based on power assignment value or random timer is used, ACO collision is seen which degrades system performance.

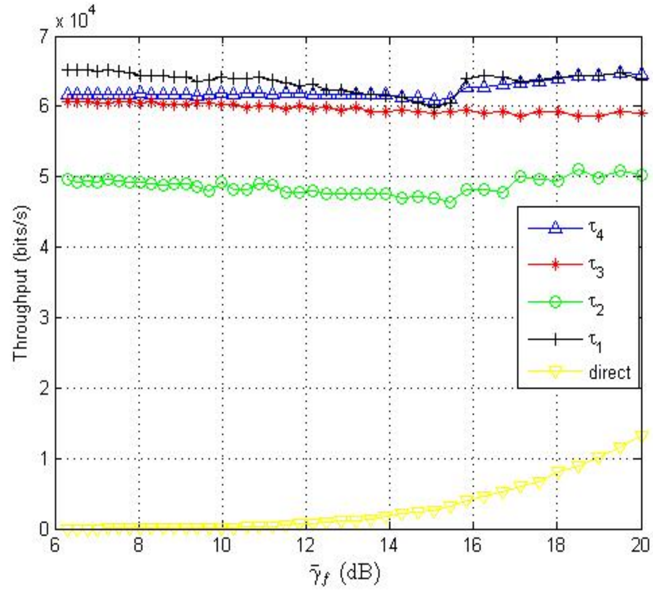

Figure 4.18: Throughput performance for different ACO timers for square grid topology

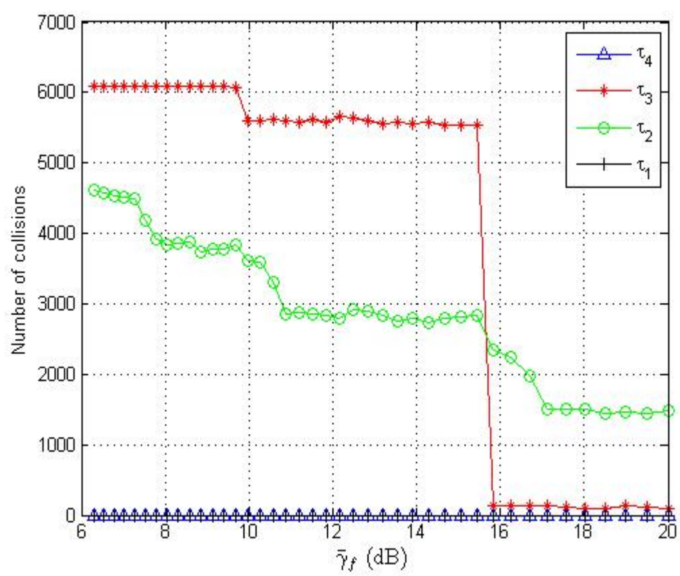

Figure 4.19: Number of collisions for different ACO timers for square grid topology

Next we check horizontal topology results. In horizontal topology, there are no two relays with same relative power assignment value. As a result, timer based on relative power assignment value performs as good as predefined timer and timer based on relative power assignment value and instantaneous RD channel power. Meanwhile, throughput decreases by 10% when random timer is used, as depicted in Figure 4.20. Collision results of horizontal topology in Figure 4.21 indicate that only random timer experiences ACO collision with this topology.

Vertical topology has all relays symmetrical with respect to both source and destination. This symmetry results in same ACO timer values, which means ACO collision. When we check vertical topology throughput results in Figure 4.22, we see that random timer gives 10% lower throughput than predefined timer scheme. All symmetrical relay pairs end up with collision at source node for all ACO packets. As we see in Figure 4.23, predefined timer and timer based on relative power assignment value and instantaneous RD channel power have no ACO collision instances, and give best results. If random timer values are used in vertical topology, experienced ACO collisions cause a decrease in througput by 10%. Timer based on rho, results in highest number of collisions and lowest throughput. When this timer is used, source node cannot receive any ACO packets and reverts back to direct transmission. The results also indicate that, throughtput of this timer is almost same as direct transmission.

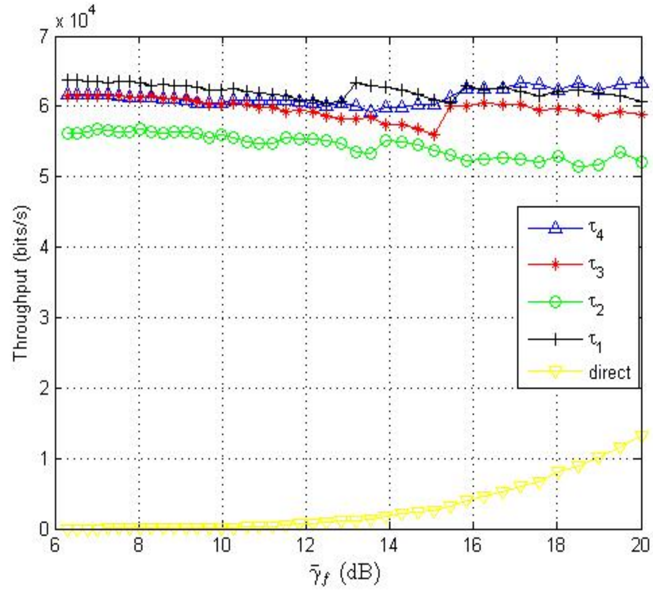

Figure 4.20: Throughput performance for different ACO timers for horizontal topology

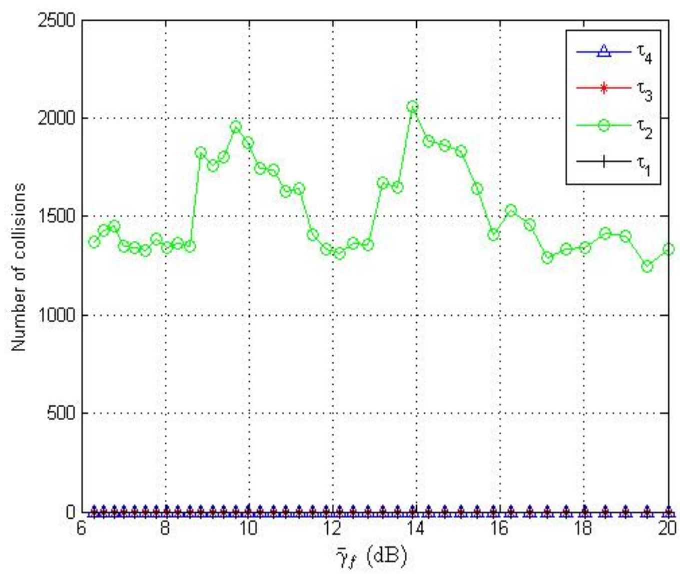

Figure 4.21: Number of collisions for different ACO timers for horizontal topology

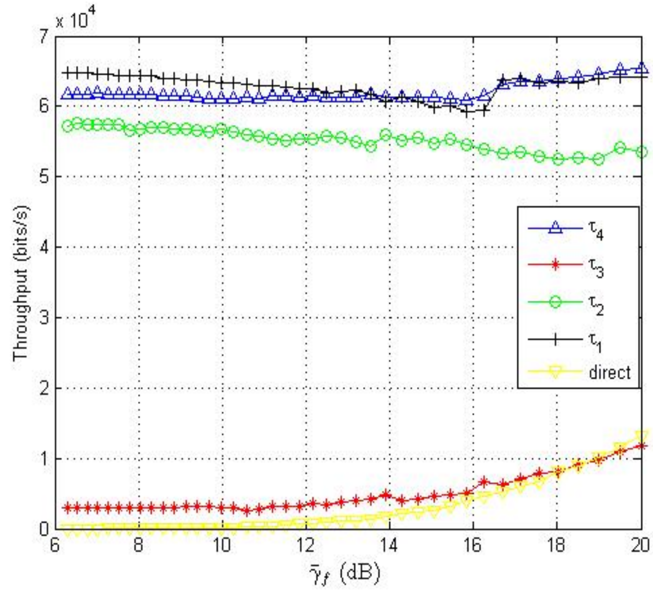

Figure 4.22: Throughput performance for different ACO timers for vertical topology

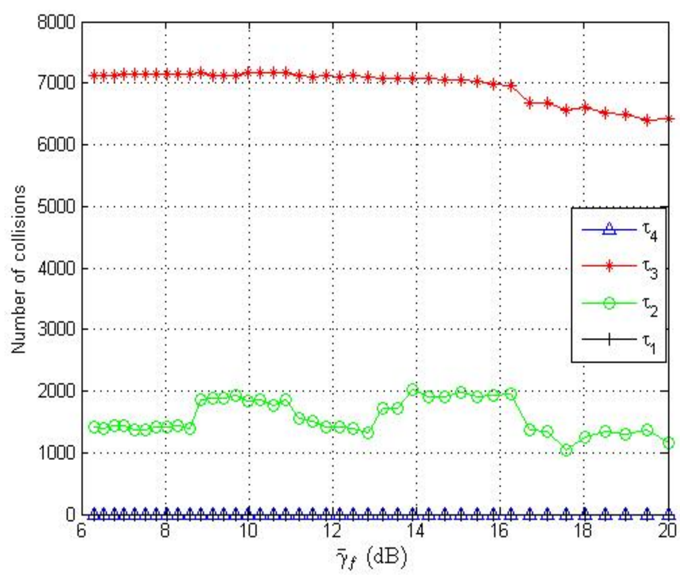

Figure 4.23: Number of collisions for different ACO timers for vertical topology

4.3.3 Effect of ACO collision resolution

Throughout this work, we analyzed various ACO timers. An optimal timer design should prevent ACO collisions. However, optimal timer design requires channel statistics and power assignment values to be provided beforehand. If such information is not present and optimal timer selection is not possible, relays would try to define their timers based on random values, which may cause ACO collision at source node. In another scenario, if two relay nodes are in symmetrical locations with respect to both source and destination, their power assignment values (ρ) would be same. If a timer based on ρ is used (for example τ_3), then ACO packets of such two relay nodes would cause collision at the source node. As a result of such ACO collisions, source node may not find any cooperators during ACO-epoch, or ACO-epoch may end up with a suboptimal cooperation set , and hence the performance of cooperative system may be degraded. As seen in these results, when ACO collisions occur in the cooperative system, proposed collision resolution model resolves ACO collision by introducing a second ACO epoch to COMAC. When ACO collisions occur, performance of the system degrades to the performance of direct system. In the following figures, performances of following scenarios are compared for vertical topology. We chose vertical topology and timer based on ρ to generate collision scenario, since ACO messages of all relays collide in this topology when timer based on ρ is used and the worst case of ACO collision scenarios is experienced. We compare the results with an optimal timer scheme, τ_4, where number of collisions is close to zero. Another figure of comparison is the direct transmission. If all ACO packets collide, then source reverts back to direct transmission. This scenario will show us possible worst case result of ACO collisions.

- D-CSPA with an ACO timer based on relative power assignment and instantaneous RD channel power (τ_4)

- D-CSPA Collision Resolution with an ACO timer based on relative power assignment value only (τ_3)
- Direct transmission

Throughput performance of COMAC CR in Figure 4.24 indicates that, collision resolution algorithm resolves ACO collisions, where throughput performance of the system decreases because of the increased time consumption. Additional ACO epoch increases the time consumed for successful transmission of a data packet and total number of successfully transmitted data packets decrease, which results in a decrease in throughput of the cooperative system. Meanwhile, even if throughput is lower than optimal timer scenario, it is much higher when compared with direct transmission.

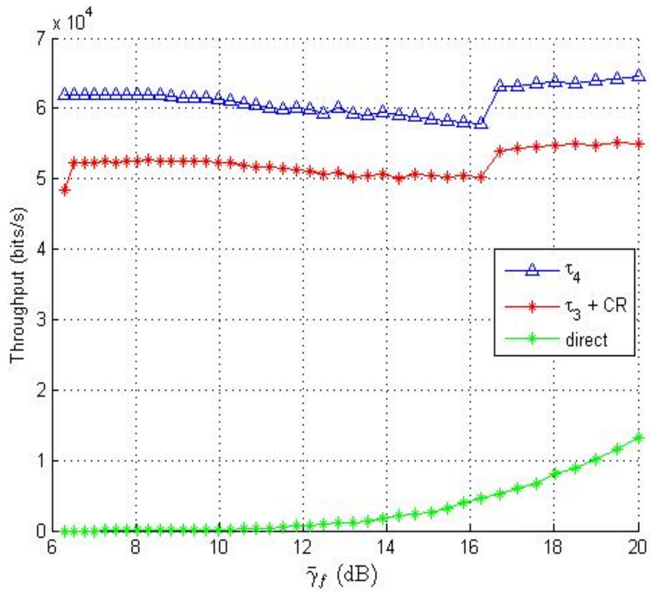

Figure 4.24: Throughput performance of COMAC with τ_4, τ_3 and τ_3 with collision resolution for vertical topology

Next we analyze MAC overhead bandwidth. Beacuse of the second ACO-epoch, total number of control packets is increased. Also, total number of successful data packets is decreased as a a result of increased RTS-ACK time duration. Therefore, MAC overhead bandwidth consumption of cooperative system increases with proposed collision resolution architecture, as shown in Figure 4.25.

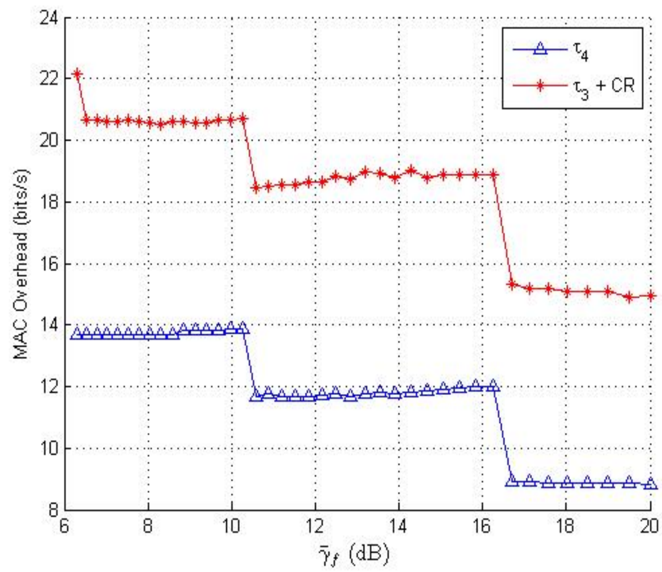

Figure 4.25: MAC overhead bandwidth of COMAC with τ_4, τ_3 and τ_3 with collision resolution for vertical topology

As a result of additional ACO-epoch duration and decreased total number of successful packets, collision resolution implementation increases average delay of the cooperative system, when compared with optimal D-CSPA. This increase can be seen in Figure 4.26.

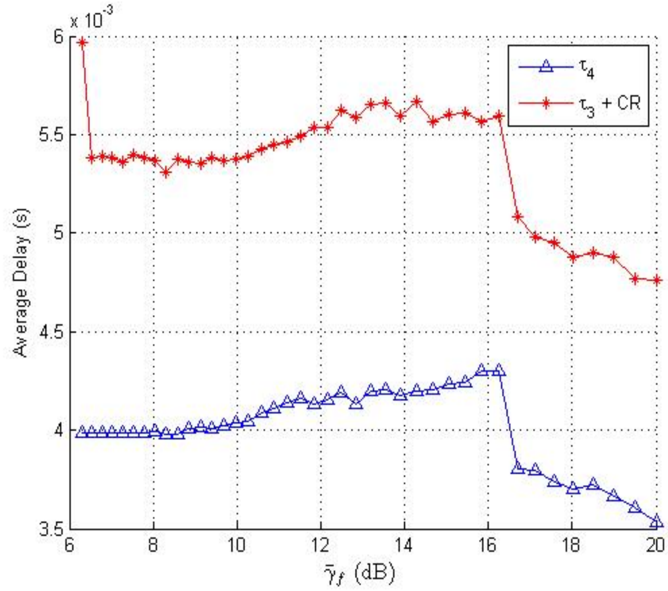

Figure 4.26: Average delay of COMAC with τ_4, τ_3 and τ_3 with collision resolution for vertical topology

4.3.4 Effect of cooperation mode

If CDMA is used in second data phase, source and relay nodes use same time period to send their data signal copy to destination. However, in TDMA nodes in cooperative system send their data signal to destination in turn. Source node sends its data signal first. Then relay nodes start sending their data signal in the order of of ACO sending. We analyze and compare energy-per-bit, average delay, MAC overhead bandwidth and Throughput performances of two cooperation modes. D-CSPA with timer τ_4 is used during simulations. We do not consider energy costs stemming from implementation details of CDMA and TDMA in these simulations, we just consider the energy cost as described with Equation (3.8) which is described in chapter 3. When we check average delay results in Figure 4.27, it is seen that CDMA mode gives flat results during simulation. TDMA has higher average delay level than CDMA. Average delay of TDMA mode increases as the number of cooperators increase.

TDMA mode consumes more time in order to send one successful packet do destination. As a result, less number of packets can be sent during total simulation period, which decreases throughput. As SD distance increases, more cooperators needed for successful transmission, and throughput decreases as the number of cooperators increase, as shown in Figure 4.28.

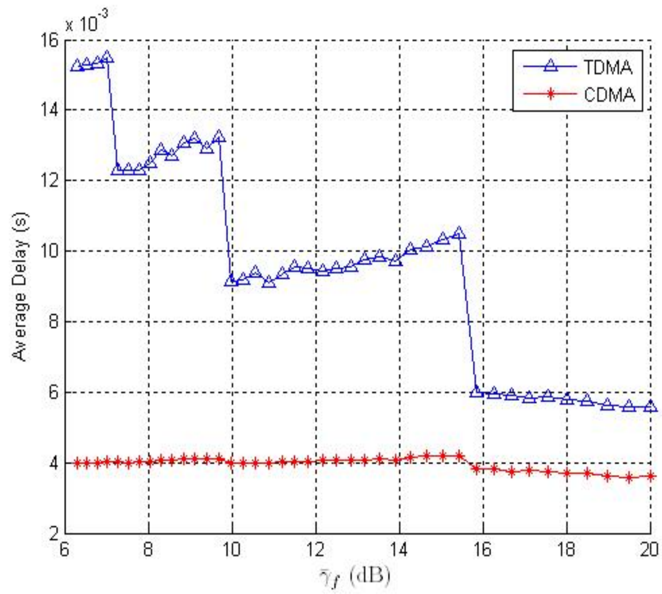

Figure 4.27: Average delay performance of COMAC with CDMA and TDMA for square grid topology

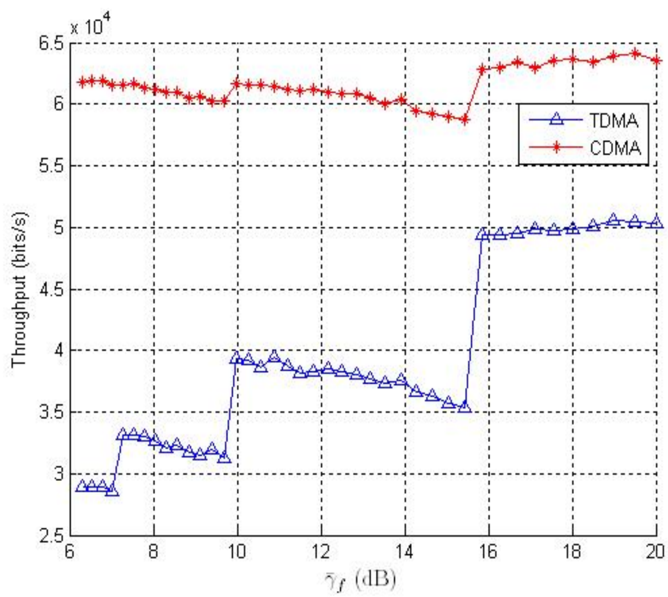

Figure 4.28: Throughput performance of COMAC with CDMA and TDMA for square grid topology

TDMA cooperation mode does not introduce any new control pakcets, and does not demand for extra control packets. As a result, number of control packets required for a successful data transmission is same in both CDMA and TDMA, as shown in Figure 4.29.

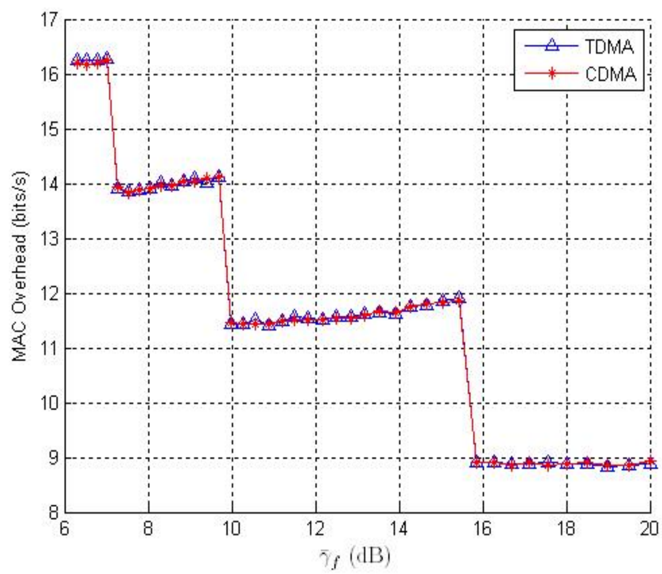

Figure 4.29: MAC overhead bandwidth of COMAC with CDMA and TDMA for square grid topology

Finally we check the energy-per-bit performance. Since energy spending of the nodes does not increase in TDMA mode, energy-per-bit level is same for both CDMA and TDMA, as in Figure 4.30.

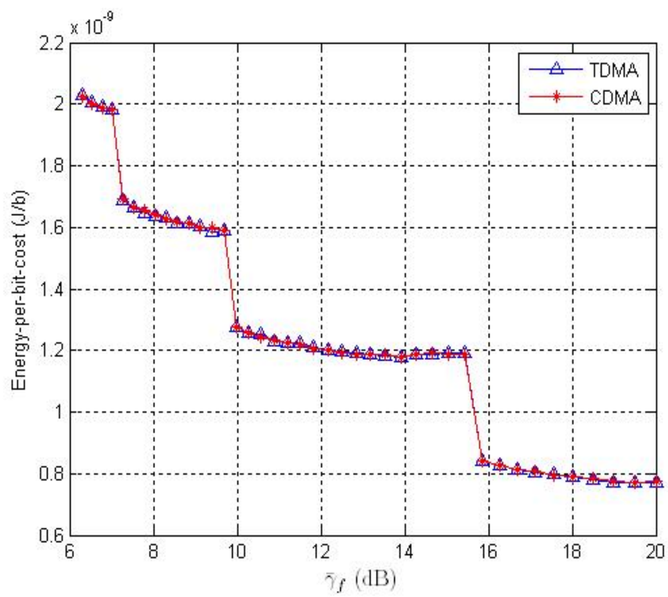

Figure 4.30: Energy-per-bir performance of COMAC with CDMA and TDMA for square grid topology

4.3.5 Effect of sleep model

In sleep model, relay nodes that do not participate in cooperation go to sleep mode, instead of waiting in idle mode. In idle mode, a sensor node keeps listening the medium, which may cause overhearing and reception of packets that are not destined to that node. Proposed sleep model keeps the relay node in sleep state if that relay node will not participate in cooperation. This mechanism is controlled by NAV timer. In order to test this feature, we used new energy model calculations already implemented in ns2. This model calculates the power spent in all four radio states: transmit, receive, idle and sleep.

In order to simulate the effect of energy model in ns2, we make use of an already implemented feature of ns2 implementation of MAC 802.11 . Using ns 2.30 version, the physical layer has full control over radio states, and it is possible to put radio into sleep state, and wake it up later. Moreover, energy consumption of nodes are traced at all times. Whenever the radio state changes, it updates the energy model to subtract the appropriate amount for the previous state. The new physical layer in ns2 provides accurate energy measurement no matter what MAC is running on top of it. Using this available feature of ns2, we could see the effect of proposed sleep model. In order to integrate COMAC with sleep feature of ns2, changes have been done in following files : mac layer mac-802_11.cc, mac-802_11.h, physical layer wireless-phy.cc, wireless-phy.h and the energy model energy-model.cc, energy-model.h

According to specifications stated in [46], CC2420 consumes 18.8 mA in receive state, 17.4 mA in transmit state, 426 μA in idle state and 20 μA in sleep state. In following simulations, power consumption is calculated as P=V*I for each radio state, which means 56.4 mW in receive state, 52.2 mW in transmit state, 1.278 mW in idle state and 60 μW in sleep state, with V=3 Volts according to [46].

We simulated sleep model using COMAC with D-CSPA algorithm and timer based on ρ and P_{rd} (τ_4).

First we check total energy consumption of the system:

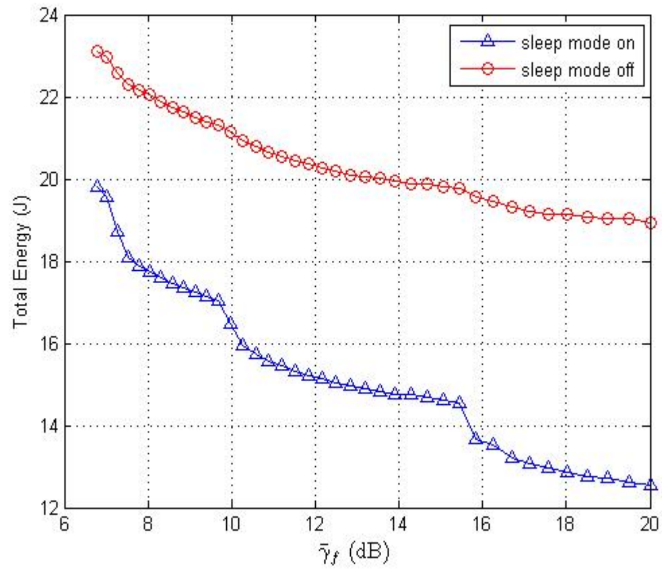

Figure 4.31: Total energy consumption of cooperative system with sleep model and without sleep model, for square grid topology

Results in Figure 4.31 indicate that energy saving of the system is almost 33% for one cooperator case, 25% for two cooperator case and 20% for three cooperator case. As the number of cooperators increase, energy saving due to sleep model decreases, as expected.

Total sleep energy of the system, depicted in Figure 4.32, is quite low when compared to total energy cost of the system, since power consumption in sleep mode is 0.1% of the power consumption in receive mode.

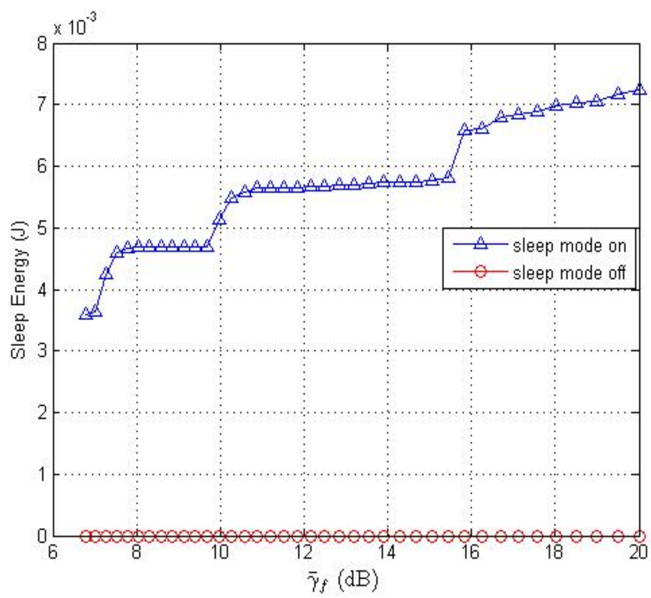

Figure 4.32: Sleep state energy consumption of cooperative system with sleep model and without sleep model, for square grid topology

Idle mode energy consumption of the cooperative system also decreases 5% in sleep model, as seen in Figure 4.33.

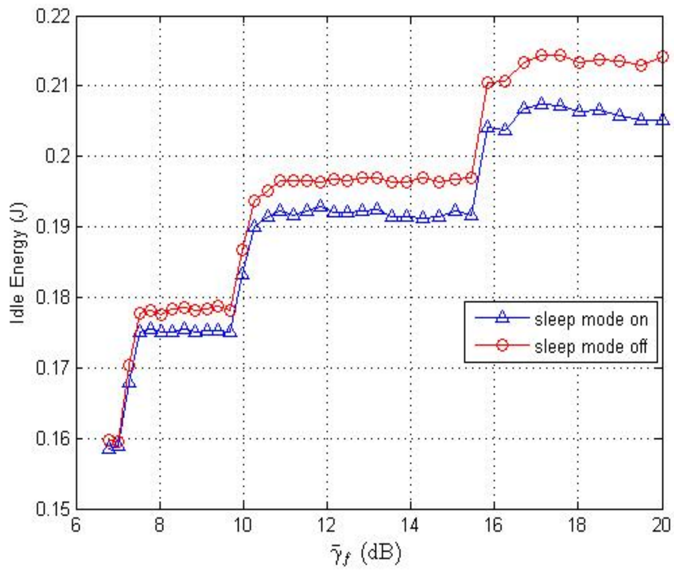

Figure 4.33: Idle state energy consumption of cooperative system with sleep model and without sleep model, for square grid topology

Most substantial energy consumption decrease is observed in receive mode. When receiving a packet, relay nodes spend as much energy as they use when they are sending that packet. A relay that does not participate in cooperation and stays in idle mode, receives ACO, $DATA_I$, $DATA_{II}$ and ACK packets unnecessarily. Sleep model saves the energy spent at these packet receptions. Figure 4.34, shows that total receive energy of the cooperative system decreases by 42% when there is one cooperator, 30% when there are two cooperators and 24% when there are three cooperators.

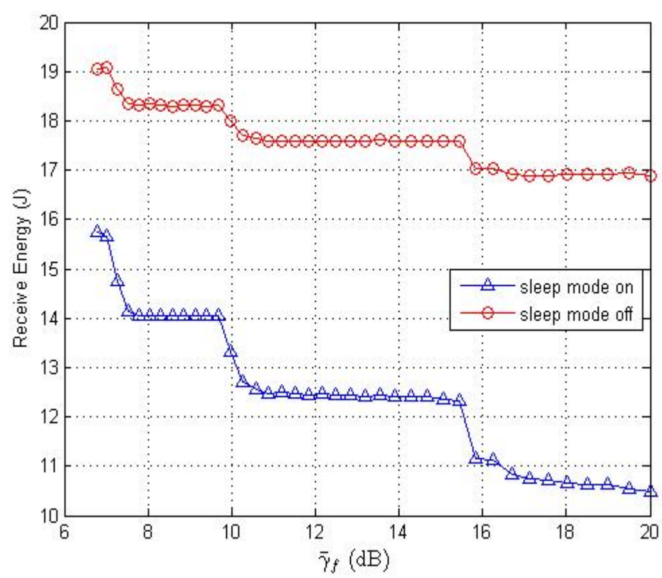

Figure 4.34: Receive state energy consumption of cooperative system with sleep model and without sleep model, for square grid topology

4.3.6 Computational Energy Consumption

COMAC protocol requires an effective cooperator selection and power assignment algorithm. In previous chapter, D-CSPA algorithm is introduced. Energy consumption and throughput performance of D-CSPA is analyzed in previous sections of this chapter. Previously depicted energy consumption calculations include the energy spent in transmit amplifiers, and transmit and receive circuitries. Here we analyze computational energy cost of cooperator selection and power assignment algorithm. Cooperator selection and power assignment algorithm, compares optimality of an existing cooperation set with a new cooperation set and decides whether new cooperation set is more optimal than the existing one. This algorithm is executed by candidate relay nodes, upon receiving a CTS message or an ACO message. Number of arithmetic operations, comparisons, variable assignments is counted. When a 16-bit microcontroller is used, addition operation is completed in 9 CPU instructions. Similarly subtraction operation is completed in 7 CPU instructions, multiplication operation is completed in 35 CPU instructions and division operation is completed in 41 CPU instructions [56]. Each instruction is assumed to be completed in one effective processing cycle. Total number of operations are determined by an internal counter that is increased according to required number of instructions of corresponding arithmetic operation as described above. We assumed that Texas Instruments TI MSP430F2274 is used as microcontroller. Energy cost per instruction of this microcontroller, working at 1MHz, is 594 pJ [54,55]. Total computational energy consumption is calculated by multiplying total number of instructions of D-CSPA algorithm with per instruction energy consumption of microcontroller. COMAC with sleep model and D-CSPA algorithm is used for simulations. 8 relay nodes are placed around the source node in a square grid topology. Computational energy consumption of the cooperative system is the cumulative sum of computational energy consumptions of all relay nodes.

Simulation results given in Figure 4.35 show that computational energy consumption follows the same pattern as amplifier and circuitry total energy consumption of the system which is given in Figure 4.31. Ratio of computational energy consumption of D-CSPA algorithm processing to amplifier and circuitry energy consumption of COMAC protocol is 1/200 when number of cooperators is 1, 1/150 when number of cooperators is 2 and 1/130 when number of cooperators is 3. D-CSPA algorithm calculates power assignment values of all relay nodes in the cooperation set and compares these calculated values with previous cooperation sets. As the number of relay nodes in the cooperation set is increased, required number of computations is also increased. When we check the simulation results, both total computational energy consumption of the cooperative system and the weight of computational energy consumption within overall energy consumption of the cooperative system is increased as the number of relays in the cooperation set is increased.

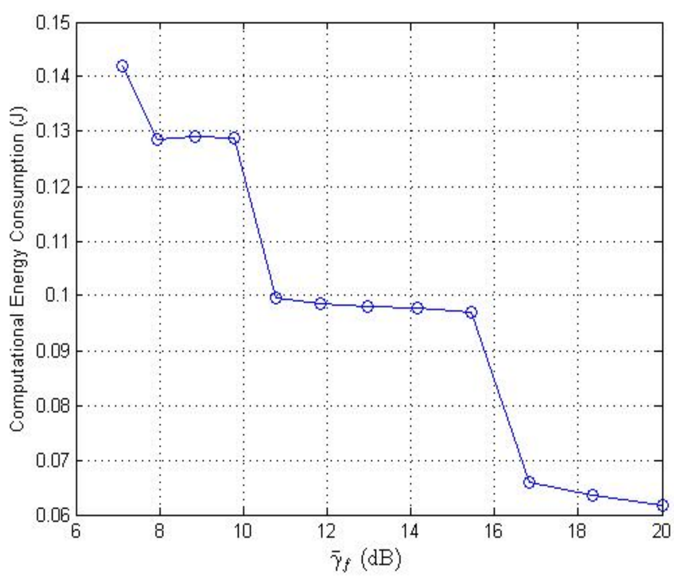

Figure 4.35: Computational energy consumption of cooperative system

4.3.7 Multiple Source Nodes

So far, we have tested performance of our protocol using single source node. Here we extend our simulation environment to include multiple source nodes. In this set of simulations, 20 nodes are randomly distributed in a 4mx4m area. Destination node is placed 14m away from the center of 4mx4m region and the location of the destination node is fixed during simulations. Number of source node candidates is increased at each step from 1 to 10. Sleep model is used during simulations, and the nodes that do not participate in data transmission neither as a source node nor as a relay node, set their radio states to sleep mode during related NAV period. Total energy consumption of the cooperative system is calculated, for each number of source nodes. 10 instances of simulations are carried out for each source node configuration. At each instance, source nodes are distributed randomly again in 4x4 region. Finally, results from 10 random topologies are averaged at each source node configuration.

In our simulation scenario, source node candidates contend for reserving medium via sending RTS packages. When one node reserves the medium, other nodes start acting as relay nodes for cooperative system. The simulations show us that, when number of source node candidates is greater than one, possible RTS collisions are experienced at the destination node. As we increase the number of source node candidates, number of RTS collisions also increase, which increases energy consumption of the cooperative system, as in depicted in Figure 4.36. Meanwhile, throughput of the cooperative system decreases as the number of source nodes in the medium increases, due to the increased number of RTS collisions, as in depicted in Figure 4.37.

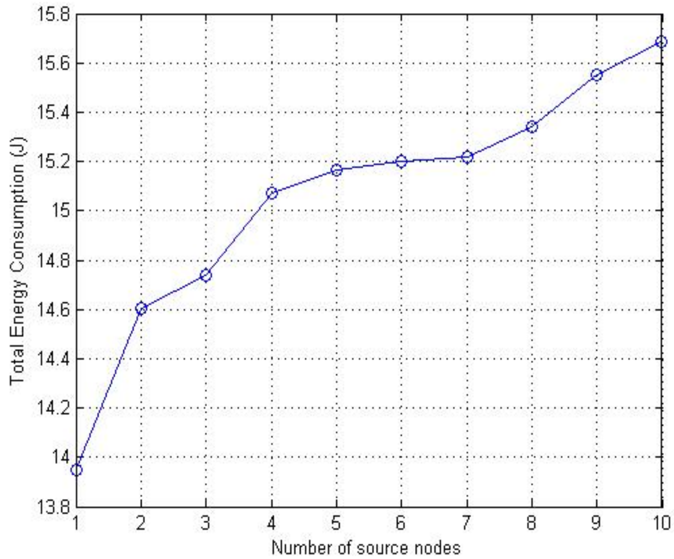

Figure 4.36: Energy consumption of cooperative system when multiple source nodes are used

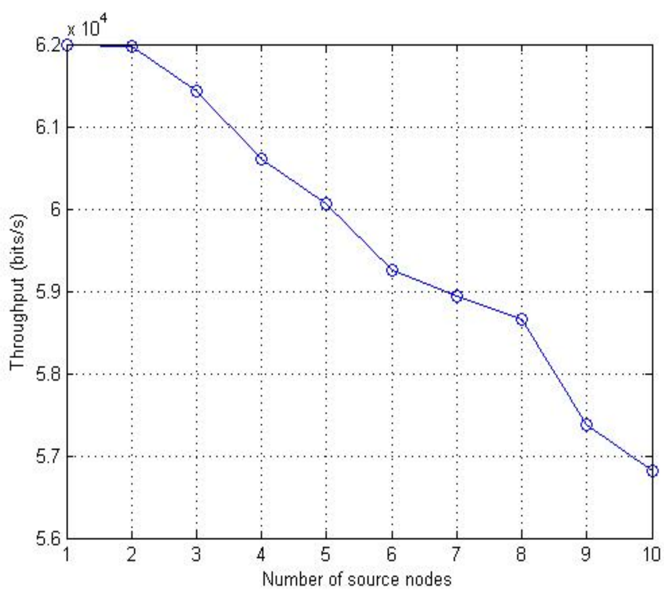

Figure 4.37: Throughput of cooperative system when multiple source nodes are used

5 CONCLUSIONS

In this thesis, we have designed a cooperative MAC protocol with distributed relay selection and power assignment mechanisms, collision resolution and sleep-awake features.

First, the cooperative protocol, COMAC is enhanced with the implementation of D-CSPA and evaluated using ns2 simulations. In D-CSPA, an optimal cooperation can be realized when relay nodes announce their cooperation decision in correct order, and when the aim is to minimize total energy consumption candidate relays with lower energy consumption should send their ACO first. Hence, real time simulation implementation of COMAC requires efficient ACO timer design. In this thesis four different timer designs are considered. Each timer necessitates certain amount of channel information and resulting gain is proportional. If exact topology and order of relay nodes are known beforehand, a predefined timer can be used. This timer gives optimal results, if channel conditions and topology of the relay nodes do not vary over time. When there is no information and estimate about the channel statistics, then a timer based on random values can be used. In this timer design, each relay node selects a random time slot and sends its ACO timer in this time slot. This timer implementation is useful in less informative cases, and gives better results than direct transmission. However, using random values causes increased number of collisions, which degrades the performance of the cooperative system. Also, relay selection does not end with energy optimal cooperation set, since decision criteria is random. If average channel statistics are available, a more intelligent ACO timer is proposed. This new timer, based on relative power assignment value, assures that relays with less energy consumption will be preferred in relay selection. A decrease in total energy consumption of the cooperative system is provided using this timer. However, since this timer is based on average channel statistics, relays that are symmetrical with respect to both source and destination have similar ACO timer values, which means that ACO collisions are observed at source node. If both average channel statistics and instantaneous channel values are available at the relay node, then a more sophisticated timer design is possible. This timer is based on two metrics, relative power assignment value, and instantaneous relay destination channel power. The former of these two metrics assures the energy minimizing relay selection order, where the latter one differentiates between relays with same relative power assignment value, by favoring the relay with better relay destination channel conditions. The simulations proved that the latest timer model gives best results in terms of energy efficiency, in cases where full channel state information is available. Throughput of the system is higher and number of collisions is close to 0.1% in this case. Consequently, each timer proposed in this work can be used in different cases, and performance of the cooperative system increases for increased amount of information about system.

Next, we have proposed a modification to existing COMAC protocol in order to overcome ACO collisions. Selected ACO timers may end up with considerable amount of ACO collisions. Simulations proved that, addition of a second ACO-epoch solved the ACO collision problem substantially. Despite 15% lower throughput and increased MAC overhead results, when compared to optimal relay selection case our proposed ACO collision resolution implementation outperforms direct transmission in all aspects.

Then, we have compared the performances of CDMA and TDMA techniques in cooperative data transmission phase. When we use CDMA, source node and cooperating relay nodes send their data signal simultaneously in one time slot. However, in TDMA, source node and relay nodes repeat data signal sequentially in consecutive time slots. Results indicate that, throughput of the cooperative system decreases by 15% with TDMA. In addition, decrease in throughput increases proportional to number of cooperators in cooperation set.

Additionally, an important component in energy consumption is handled. In the existing protocol, relay nodes that are not part of cooperative set stay in idle state till the end of cooperation. However, a relay in idle mode spends 20 times more energy than same relay in sleep mode. We have modified the existing COMAC protocol to support sleep mode of the relay nodes, when they decide that they will not participate in cooperation. The results show that up to 33% savings in total energy consumption is possible. Despite increased energy efficiency, throughput of the cooperative system remains unchanged.

Relay nodes consume energy when they are processing the information, gathered from cooperative system, in order to compute cooperation decision algorithm. This computational energy cost is calculated, based on number of operations in the cooperation decision algorithm and energy consumption of microcontroller as stated in related specifications. The results indicate that, computational energy cost is 1/200∼1/130 of total energy consumption, depending on number of relay nodes in the cooperation set.

Last but not least, performance of the protocol is tested under multiple source node scenario, where several source node candidates contend to send information to a common destination. The node that reserves the medium first, sends its data and other nodes act as relay nodes. This contention mechanism increases the number of RTS collisions experienced at the destination node. As a result, energy consumption of the cooperative system increases and throughput decreases.

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