Impact of MAC Protocol on Efficiency of Wireless Distributed Computing Applications

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***Abstract*— This paper considers the problem of computing the efficiency impact of Media Access Control (MAC) protocol on a Wireless Distributed Computing application. Test cases were set up to consider four MAC protocols (CDMA, FDMA, TDMA and CSMA) in two different network topologies. It was found that a useful strategy for extracting meaningful comparisons was to calculate the crossover point between processor limited operation and transport limited operation. The crossover point, a processing load factor measured in seconds per megabyte of raw data, could then be plotted as a function of the volume of raw data. The resulting plot allows direct comparison of efficiency in terms of both the size of the processing task and the size of the transport task.**

Keywords- WDC, Wireless Distributed Computing, MAC, Media Access Control

I. Introduction

Wireless Distributed Computing (WDC) is an emerging area of research in cases where the owners of a network wish to leverage the processing capabilities of multiple nodes to complete a complex task [10],[11]. Work in this area has included research into energy efficiency [8], task allocation and scheduling [5],[9], cross-layer resource allocation [6], the impact of channel variations [7], protocols to facilitate resource discovery [9], etc. Although individual Media Access Control (MAC) protocols have been evaluated as an aspect of specific research, there does not appear to be a general comparison between MAC protocols in terms of impact on efficiency, nor do there appear to be tools that would facilitate such a comparison.

To begin filling this need for generalizing the comparison process, this paper reports on comparative analysis done between four broad classes of Media Access Control protocols. The analysis varied the topologies in which they are used and studied the implications of these protocols and network topologies on efficiency of Wireless Distributed Computing applications. Although only a few specific results can be treated in this paper, the methodology for comparison, and the nature of metrics used for comparison will be of use to others in the Wireless Distributed Computing community.

Section II of this paper discusses background into how the evaluations were conducted. It begins with information about the four Media Access Control protocols. The topologies used to examine performance differences are then presented. This is followed by commentary on frequency planning, duplexing and RF gender. The final section in the background section is the methodology used to calculate link capacity.

Section III presents two network topologies, Hub/Spoke and Round Robin, and discusses ways that each topology and MAC protocols use resources, and how that affects efficiency. 10 cases are generated to provide the necessary contrast between the four classes of Media Access Control protocols. Efficiency calculations for each of the 10 cases are presented in section IV. Analysis is conducted in Section V, and some conclusions are drawn in Section VI.

II. Background

The three resources that constrain all MAC protocols are: bandwidth, time, and spatial separation. Each protocol makes a slightly different use of these resources, and is affected differently by the topology of the network, the distance between nodes, and relative speed between nodes. Those differences result in differences in efficiency of the data delivery process which, in turn, affects the achievable efficiency of a Wireless Distributed Computing application.

WDC processing is considered in this paper to be a three step process: 1) a Master Node sends raw data to other processing nodes, 2) each of those nodes processes the data, and 3) each processing node returns results to the Master Node. For a WDC application, efficiency can be defined as the percentage of time that nodes spend processing data vs waiting for data to be delivered; if the node can process data full time, efficiency could be considered to be 100%.

This paper attempts to normalize the comparison of different Media Access Control protocols to the WDC application scenario by applying the same constraints to each protocol. The first constraint is that the same RF spectrum is available in each case. That spectrum must be shared with other WDC groups that are presumed to be in the vicinity (i.e. RF frequency planning must be done). The second constraint is that the comparison is based on Shannon capacity limits rather than the achievable data rates of individual modulation and error correction schemes. Since we will consider some extreme cases in terms of distances and relative velocities, a

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third constraint is that the calculations include guard bands and guard times appropriate for each approach.

A. Media Access Control Protocols

Four Media Access Control Protocols are considered in this section. Each has a slightly different method for using time and frequency resources.

1) ***Code Division Multiple Access (CDMA)*** channelization is created by coding. Systems use the full allocated frequency band at all transmitters (less stop bands between their allocated frequency range and adjacent frequency allocations). However, since they either use frequency hopping or Pseudo-Random Noise sequences, the effective data rate for any given channel is a fraction of the total data sent.

2) In ***Frequency Division Multiple Access (FDMA)*** systems, channelization occurs through frequency. So, in addition to Stop Band losses at the edge of the frequency band, there are also (frequency) Guard Bands between each channel.

3) In ***Time Division Multiple Access(TDMA*)** systems, each transmitter uses the full frequency range (less Stop Bands). Each transmitter is given a slot (or slots) to send data. Between each time slot, there is a guard time that is dependent on topology and distance between nodes.

4) In ***Carrier Sense Multiple Access (CSMA*)** systems, transmission is also separated by time. However, since the time for transmission from each node is unscheduled, the guard time is based on a protocol that sends additional messages across the system.

B. Topology

One of the first questions relating to the impact of the Media Access Control protocol is the topology of the network. This paper will consider two different topologies. The first type of topology will be called Hub/Spoke. The second type will be called Round Robin. In both cases, a "Master Node" is the originator and final destination of all data transmitted in the network.

1) Hub/Spoke with Omni-Directional Antennas

In the Hub/Spoke case, the Master Node sits at the center of a group of six other nodes. As indicated by the arrows in Figure 1, the Master Node sends data directly to each node, and receives data directly from each other node. Assuming the use of an Omni-directional antenna means that the Master Node broadcasts data to all nodes, and each node has to decide whether that data pertains to it or not

The Hub/Spoke Topology forms one extreme of the system types that are considered in this paper. For calculation purposes, it is assumed to be on the small side, with a radius of 100 meter. Its nodes are assumed to be moving at no more than pedestrian speeds.

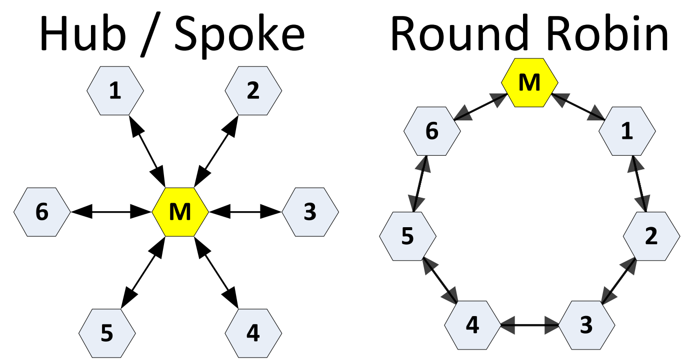

Figure 1 Topologies Considered

2) Round Robin with Directional Antennas

Rather than having the Master Node in range of every node, it is also possible for all nodes to form a linear topology where each node maintains a data link with two other nodes, and the chain of nodes closes on itself to form a ring. This will be called Round Robin in this paper. It is illustrated in Figure 1. It is assumed that the radius of this system is 500 Km (~450 Km between nodes). It is also assumed that this system must accommodate satellite speeds.

C. Frequency Planning

In considering the use of spectrum, this paper assumes that the system consists of seven nodes (one Master node and 6 processing nodes.). When omni-directional antennas are used with FDMA, TDMA or CSMA systems, frequency planning must divide the total band into 7 sub-bands.

D. Duplexing

The issue of frequency planning has one other dimension. This is the question of whether the transmitter and receiver use the same frequency. When transmitting, the signal from the transmitter can overwhelm the receive signal if they use the same frequency. This is because the receive signal could be 80 dB down from the transmit signal, and the isolation between transmit and receive paths is often much less than that.

There are two ways to get around the problem of interference from one's own transmitter. The first is to transmit and receive at different times (Time Division Duplexing or TDD). The second is to transmit and receive at different frequencies (Frequency Division Duplexing or FDD). Whether TDD or FDD is in use affects the way that frequencies are allocated. Both TDD and FDD cases are considered in this paper. Figure **2** shows which cases implement TDD and which implement FDD.

E. Gender

It has already been indicated in section II.D that transmitting and receiving at the same frequency is not possible when using the same antenna. When there are multiple antennas on the same node, whether it is possible or not for one antenna to transmit at the same frequency as another antennas receives depends on the separation distance between antennas. The minimum separation distance is often in the tens of meters, even for highly directional antennas. So, for Round Robin systems in this analysis, it will be assumed that no receivers at a node can receive at the same time and frequency as any transmitter at that same node.

A common solution to this problem is to enforce a transmit frequency policy. Each node can transmit at the same frequencies for any of its antennas but must use a different frequency for receiving. Typically all transmitters use the same transmit frequency, and all receivers use the same receive frequency, so the combination is called a gender. With two frequencies available, two genders are possible. More genders are possible, providing that appropriate duplexers can be built[1]. This paper will consider 4 and 8 gender systems in addition to 2 gender systems.

F. Capacity Calculatiions

This section provides an overview of the calculations used to estimate the data rates achievable by the different systems, and the Guard Bands and Guard Times. These calculations will be based on the Shannon capacity of the channel.

1) CDMA

The calculation of channel capacity is a two-step process. First, the capacity of the data link is calculated as if the channel had been FDMA, then the spreading factor is applied. A spreading factor of 64 is assumed for the Hub/Spoke case. A spreading factor of 8 is also assumed for one of the Round Robin cases to provide contrast.

2) FDMA Capacity:

The formula for calculation of FDMA [2] data rate is given below:

$$C = Wlog2\left(1+\frac{s}{WNo}\right)(bps)$$

Where: C is Channel Capacity in bps
W is the bandwidth of signal in Hz,
N_o is the noise power density,
S is the signal power

To derive the channel capacity, we first subtract stop bands from the band edges, then divide the remaining bandwidth into the required number of channels and subtract the Guard Bands. Then the formula above is used to calculate the channel capacity. A discussion of Guard Bands follows.

FDMA systems are usually limited by adjacent channel interference. Adjacent Channel Interference depends on the carrier spacing and signal bandwidth. Carrier spacing must be adequate to accommodate for frequency variations. A guard band is required to ensure proper operation of the system. The amount of guard band depends [2], [3], [4] on oscillator drift, oscillator wander & jitter, and carrier Doppler shift.

- Frequency uncertainty due to Doppler shifts:

When a receiver is moving towards the source or away from the source, then the received frequency is higher or lower than when transmitted. This resulting change in frequency is known as the Doppler shift. If f_0 is the carrier frequency then the Doppler shift is given by

$$f_d = \frac{-f_0}{c} v.\cos\theta$$

- Frequency uncertainty due to drift and wander:

For the drift and wander, we consider the standard straight line approximation for drift due to aging. Based on the straight line model [2], assuming an upper bound of one part in 10^7 per month for the aging rate of a high quality quartz oscillator, the expected frequency departure is estimated to be not more than about 65 Hz, in one month's time. Table 1 lists the Guard Bands calculated for different speeds, frequencies, and distances.

Table 1 FDMA Guard Band Calculations

Distance	100m	100 km	500 km
Frequency	2 GHz	11 GHz	11 GHz
Bandwidth	10 MHz	10 MHz	10 MHz
Speed	3 m/s	250Miles/Hr (111.76m/s)	7000 m/s
Doppler Shift	20 Hz	745 Hz	46,669 Hz
Drift and Wander [2]	65 Hz	100 Hz	150 Hz
Guard band	85 Hz	845 Hz	46,819 Hz

3) TDMA:

In TDMA systems, each user is allocated the full channel bandwidth, part of the time. Users transmit a burst of data in a pre-assigned timeslot. Only one user transmits at a given time and each user receives the full performance of the channel when they have the time slot, whether they need it or not. The calculation of channel capacity for TDMA systems follows the model of first calculating the maximum data rate supported by the operational band (less stop bands at the edges), then dividing up into time slots, and subtracting Guard Times. Important points for TDMA calculations follow.

A TDMA system transmits a burst for a time dependent on the number of users (N). Assuming equal data rate allocations, the duration of the burst is 1/N seconds (adjusted for overhead). Only one user transmits at a time, but each user has access to the full bandwidth channel performance when it

[1] The problem of isolation between transmit & receive frequencies is not trivial. However, 4 and 6 gender FDMA systems are under development.

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is their turn to burst. The peak transmit power during a burst is N times the average signal power (S) in order to accommodate burst.

The capacity of an ideal TDMA system [2] is

$$C = \left(\frac{1}{N}\right) W \log 2\left(1 + \frac{NS}{WN_o}\right) bps$$

In practical systems, the capacity and performance are limited by time uncertainty between user timeslots and bursts.

TDMA Guard times:
Guard time calculations are summarized in

Table 2. TDMA guard time [2], [3], [4] depends on the maximum cell size and the speed of light (C).

$$Guardband = \frac{CellRadius}{c}$$

Table 2 TDMA Guard Band Calculations

Distance	100m	100 km	500 km
Frequency	2 GHz	11 GHz	11 GHz
Bandwidth	10 MHz	10 MHz	10 MHz
Speed	3 m/s	111.76m/s	7000 m/s
Guard bands	0.333 usec	333.333 usec	1666.6667 usec

4) *CSMA*

Data rate calculations for CSMA systems are the same as those described for TDMA systems except that there is no channelization. The guard time in a CSMA system is protocol and preamble based. The protocol will have a certain number of messages that are sent and received. (e.g. CTS/RTS/ACK). After a protocol exchange a certain number of packets can be exchanged without requiring another preamble. The preamble is equal to the transit time across the network (i.e. distance/speed of light). So, the exchange could look like the following:

Preamble – Protocol Packet (e.g. CTS)
Preamble – Protocol Packet (e.g. RTS)
Preamble – Protocol Packet (e.g. ACK)

For our calculations, the number of packets sent is 3 and the preamble length is equal to the time needed to traverse the network. The message size is chosen to be 110 Bytes.

III. Channel Contention

A. *Hub/Spoke Topology Cases*

10 cases were considered for this analysis. Figure **2** illustrates which cases apply to which Media Access Control mechanism.

Omni Hub/Spoke	Data	Duplexing	CDMA	FDMA	TDMA	CSMA
Case_1	Unique/Node	TDD				
Case_2	Unique/Node	FDD				
Case_3	Common/Node	TDD				
Case_4	Common/Node	FDD				
Case_5	Unique/Node	FDD				
Directed Round Robin	**Direction / Gender**	**Duplexing**	**CDMA**	**FDMA**	**TDMA**	**CSMA**
Case_6	One-Way	FDD				
Case_7	1 Gender	TDD				
Case_8	4 Gender	FDD				
Case_9	2 Gender	FDD				
Case_10	8 Gender	FDD				

Figure 2 **Application of Cases to MAC Protocol**

Each of the cases is described and visually represented using a diagram that illustrates what happens in the channel (usually the left hand side of diagram), and what happens in the time and frequency domains (usually the right hand side of diagram). The time axis has been chosen as the vertical axis, and frequency or channel as the horizontal axis in these diagrams. Note that the time axis is not to scale. So, while it provides an indication of the packet scheduling relationship on different links, it does not indicate the actual timing. The actual time depends on actual processing time, and achievable data rate (which varies between Media Access Control protocols).

1) *Case 1: TDD/TDMA or TDD/CSMA*

The interpretation of Case 1 is as follows. There is a Hub/Spoke topology with the Master Node at the Center. The Master Node transmits to each node individually. Figure **3** is illustrated as if a single TDMA time slot was used to deliver traffic, and processing (shown in yellow) began immediately. The start times for processing at each node are staggered by the arrival time of the last packet to each node. Case 1 applies to TDMA and CSMA systems.

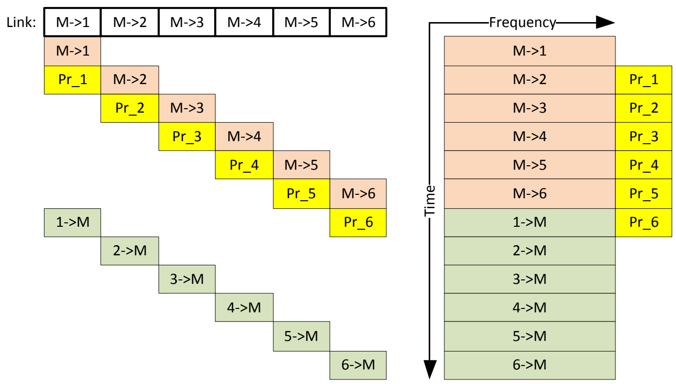

Figure 3 Case 1: Hub/Spoke TDD/TDMA or TDD/CSMA

2) Case 2

The interpretation of Case 2 is as follows. There is a Hub/Spoke topology with the Master Node at the Center. Similar to Case 1, the Master Node must send data independently to each node, and receive data independently from each node. However, it employs a different frequency for sending than for receiving. So, while it can only send or receive from one node at a time, it can both send and receive at the same time. Case 2 applies to TDMA only.

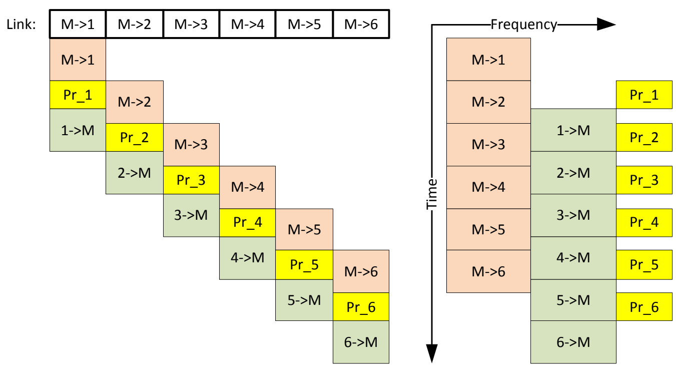

Figure 4 Case 2: Hub/Spoke FDD / TDMA

3) Case 3

The interpretation of Case 3 is as follows. There is a Hub/Spoke topology with the Master Node at the Center. The data that is sent by the Master Node can be broadcasted to all nodes simultaneously. Each can start working on that data immediately. The replies from each node must be received independently by the Master Node. As with Case 1, this applies to TDMA and CSMA.

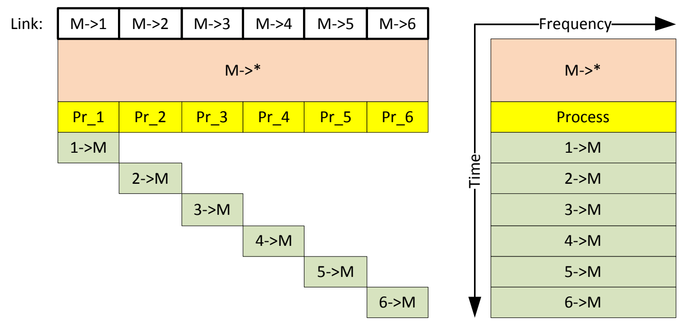

Figure 5 Case 3: Hub/Spoke TDD/TDMA or TDD/CSMA with Broadcast Conditions

4) Case 4

The interpretation of Case 4 is as follows. There is a Hub/Spoke topology with the Master Node at the Center. There are seven frequencies, one for each node. All nodes work on the same data so when the Master Node transmits, all nodes receive the data simultaneously and begin work immediately. All nodes can send their replies to the Master Nodes simultaneously by using their own transmit frequencies. Case 4 applies to FDD/FDMA systems

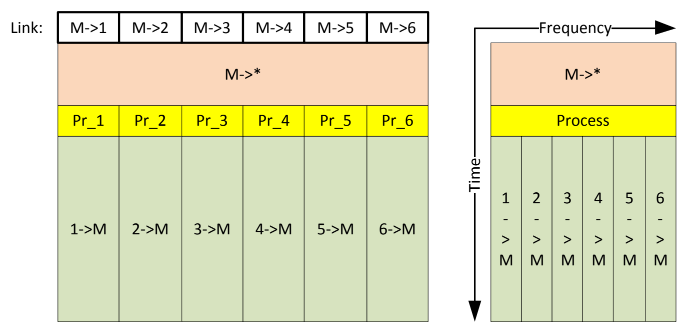

Figure 6 Case 4: Hub/Spoke FDD/FDMA With Common Data

5) Case 5

The interpretation of Case 5 is as follows. There is a Hub/Spoke topology with the Master Node at the Center. The data that each node processes is unique. To allow it to be sent or received at the same time, there are multiple transmit frequencies or CDMA channels (12 for FDMA and 16 for CDMA). Case 5 applies to FDMA and CDMA systems.

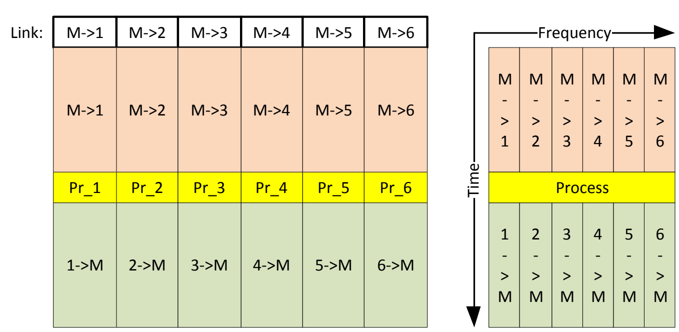

Figure 7 Case 5: Hub/Spoke FDD/FDMA or CDMA with Unique Data

B. *Round Robin Topology Cases*

1) *Case 6*

The interpretation of Case 6 is as follows. There is a ring of 7 nodes, each with a pair of data links connecting it to its neighbor around the ring. Data is transmitted by the Master Node in one direction around the ring, and is received, after processing, by having each node transmit in the same direction around the ring. To accommodate simultaneous transmission between each node, four genders are used. Case 6 applies to CDMA and FDMA systems. The frequency usage is illustrated in Figure 8. A representation of the required overlap to achieve efficiency is illustrated in Figure **9**.

The reason for four genders is that the number of nodes around the ring is odd (each hop needs to swap genders for transmit and receive so only when the number of nodes in a ring is odd can the loop be closed with two genders). The four genders are illustrated by two data links on the right hand side of Figure **9**. Two genders (Tan and Green) are used as the Transmit and Receive frequencies on most links. One data link (between nodes 3 and 4) uses the Purple and Yellow frequency bands instead. Note that the colors chosen for the illustration of channels on the left hand side could be taken to mean the color assigned to the transmit frequency in one direction around the ring.

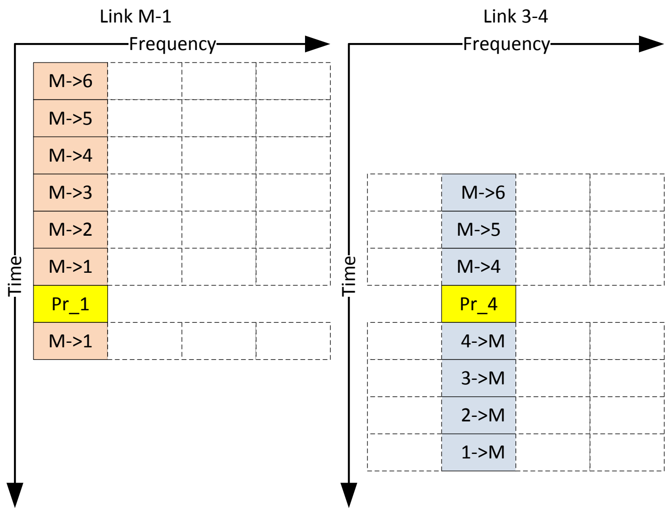

Figure 8 Case 6: Frequency/Time Use

Note here that while the Hub/Spoke cases were illustrated with the channel conditions on the left and frequency/time domain conditions on the right, the Hub/Spoke cases effectively had a single channel. The Round Robing cases have multiple channels, one for each hop around the ring. The time/frequency domain conditions for only two of the channels are shown in Figure 8.

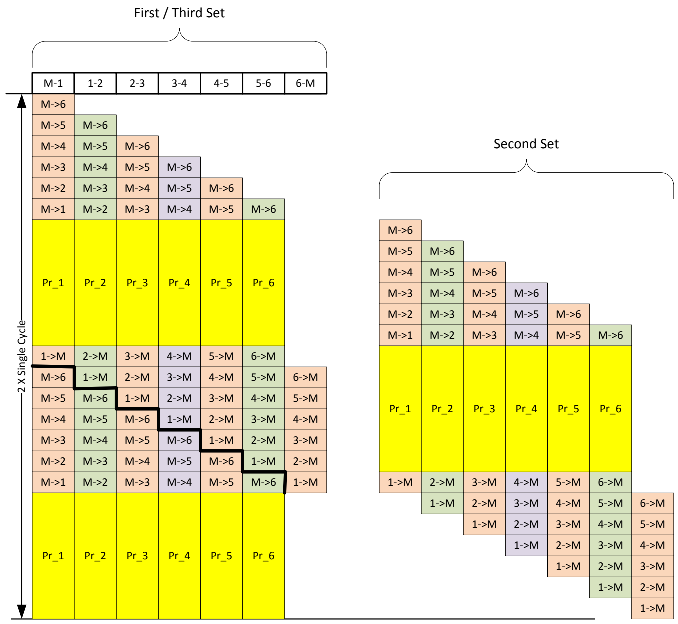

Figure 9 **Case 6: Round Robin Scheduling of FDD/FDMA or CDMA with Unidirectional Transit Around The Ring.**

2) *Case 7*

The interpretation of Case 7 is as follows. There is a ring of 7 nodes, each with a pair of data links connecting it to its neighbor around the ring. As opposed to using a different frequency as in Case 6, the strategy here uses the same frequency at all nodes. Time Division Duplexing is required at each node, and it is assumed that interference concerns are limiting adjacent nodes from transmitting simultaneously. The strategy for sending data to all nodes is to send it in both directions around the ring. This case applies to TDMA and CSMA systems.

The frequency and time usage is illustrated in Figure 10. Scheduling to achieve pipelining of transmission and processing tasks is illustrated in Figure **11**

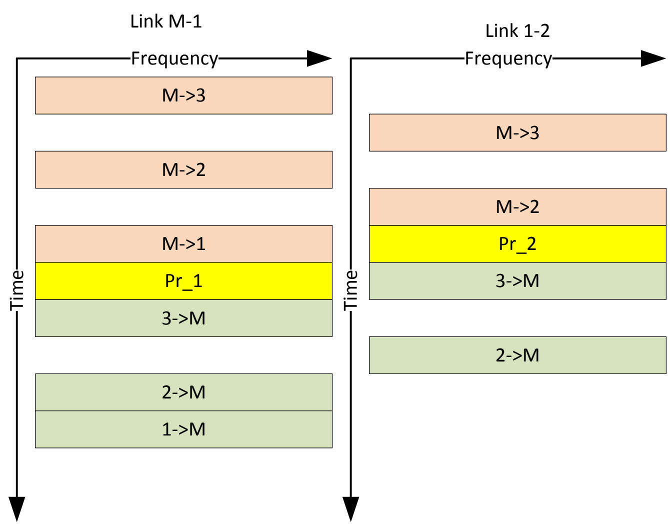

Figure 10 Case 7: Frequency / Time Use Case Example

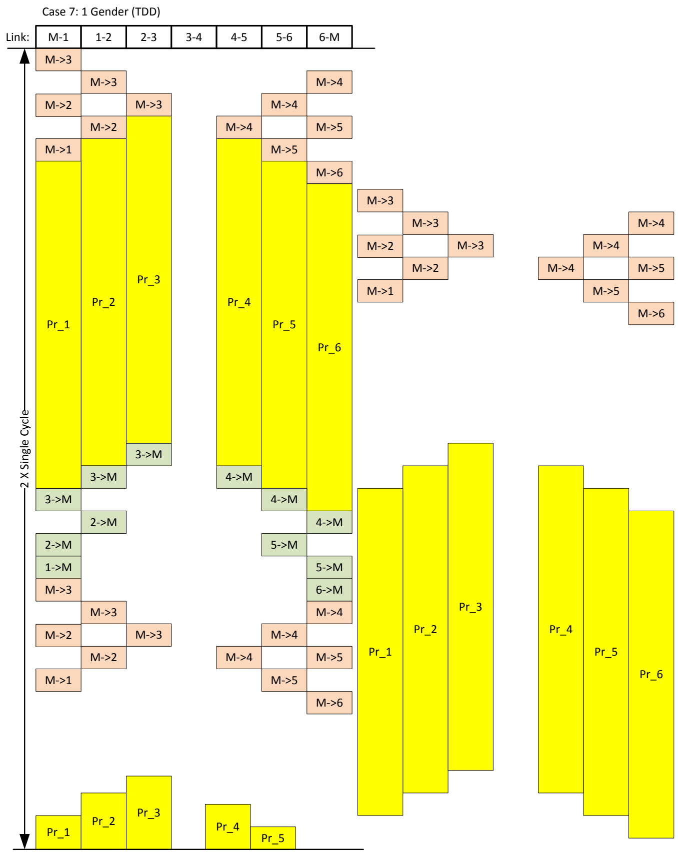

Figure 11 **Case 7: Round Robin Scheduling of TDD/TDMA or CSMA**

From a visual perspective, this case is illustrated as if the processing time were much longer than the transmission time.

3) *Case 8*

The interpretation of Case 8 is as follows. There is a ring of 7 nodes, each with a pair of data links connecting it to its neighbor around the ring. As opposed to a uni-directional transport around the ring, data is sent by the Master Node in both directions. Four Genders are used to ensure connectivity around the ring. Case 8 applies to FDMA systems. The left hand side of Figure **12** shows scheduling and the right hand side illustrates the time and frequency planning. Note that cases 9 & 10 use the same scheduling strategy.

Case 8/9/10 Scheduling

Link:	M-1	1-2	2-3	3-4	4-5	5-6	6-M
	M->3						M->4
	M->2	M->3				M->4	M->5
	M->1	M->2	M->3		M->4	M->5	M->6
	Pr_1	Pr_2	Pr_3		Pr_4	Pr_5	Pr_6
	1->M	2->M	3->M		4->M	5->M	6->M
	2->M	3->M				4->M	5->M
	3->M						4->M

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Figure 12 **Cases 8/9/10: Round Robin Scheduling**

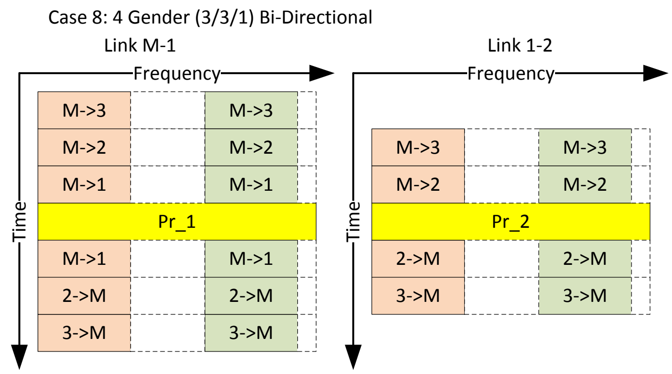

Figure 13 Case 8: Frequency /Time Usage: FDD/FDMA 4-Gender

4) *Case 9*

The interpretation of Case 9 is as follows. There is a ring of 7 nodes, each with a pair of data links connecting it to its neighbor around the ring. As opposed to using 4 Genders as in Case 8, the system uses only 2 Genders and assumes that the link between nodes 3 and 4 is not used (so does not create a problem). Case 9 applies to FDMA systems. The frequency and time usage of this case are illustrated in Figure **14**. The scheduling strategy is illustrated in Figure **12**.

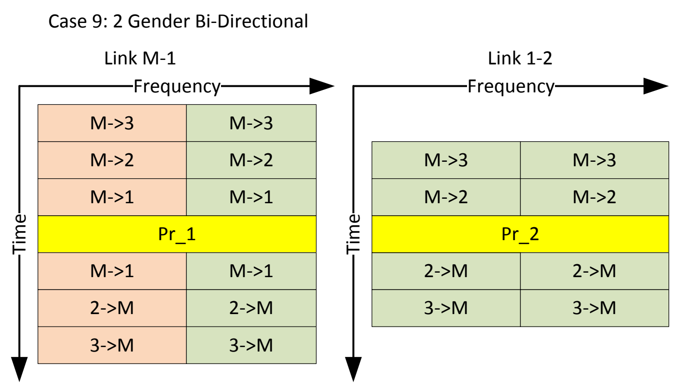

Figure 14 **Case 9: Frequency / Time Usage: FDD/FDMA - 2-Gender**

5) *Case 10*

The interpretation of Case 10 is as follows. There is a ring of 7 nodes, each with a pair of data links connecting it to its neighbor around the ring. As opposed to using only 4 Genders, 8 Genders are used. Although Case 10 could apply to FDMA systems, it is included here to illustrate CDMA systems that must have 8 channels. Figure 15 illustrates the Frequency / Time usage and Figure **12** illustrates the scheduling strategy.

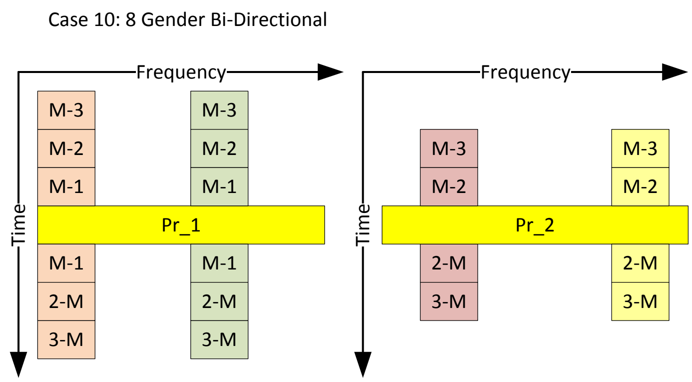

Figure 15 Case 10: Round Robin CDMA 8-Gender

IV. PROCESSING EFFICIENCY ANALYSIS

To this point in the paper, each of the Wireless Distributed Computing cases has been considered as a stand-alone activity. A point of interest is where efficiency becomes 100%, or in other words where the processing activity at each node takes the same time as the communications task so the two can be pipelined together.

$$T_{Rcv} = \frac{B_{OB} \cdot K_{Overhead}}{R_{Data}}$$

$$T_{Respond} = \frac{B_{OB} \cdot K_{Compress} \cdot K_{Overhead}}{R_{Data}}$$

$$B_{OB} \cdot L_{Proc} = \frac{B_{OB} \cdot K_{Comp} \cdot K_{OH}}{R_{Data}} + \frac{B_{OB} \cdot K_{OH}}{R_{Data}}$$

Where:
B_{OB} = Bytes outbound (i.e. bytes to be processed)
L_{Proc} = Processing Load Factor
K_{OH} = Overhead of transmission media
K_{Comp} = Ratio of outbound bytes processed to response bytes ($B_{OB} * K_{Comp} = B_{Response}$)
R_{Data} = Transmit data rate

At the crossover point, we can calculate the minimum processor load factor, i.e. the minimum task complexity in Seconds/MByte needed to keep the processor fully occupied.

$$L_{Proc} = \frac{K_{OH}\left(K_{Comp} + 1\right)}{R_{Data}}$$

It should be noted that K_{OH} is a function of B_{OB}. The overhead of sending out 10 bytes is not the same as the overhead of sending out 10,000 bytes, so since K_{OH} is a multiplier, its value changes.

A. Hub/Spoke Cases

Cases 1-5 are Hub Spoke cases. It is assumed that they are using an omni-directional antenna and that they are relatively close (100 m), traveling no faster than pedestrian speeds. The data rates calculated for the assumptions we are using in this paper are shown in Figure 16. The Processor Load Factor crossover points are illustrated in Figure **17** and Figure **18**.

Hub/Spoke	Case 1	Case 2	Case 3	Case 4	Case 5
CDMA				361,910	361,910
FDMA				472,502	236,153
TDMA	472,671	236,321	472,671		
CSMA	472,671		472,671		

Figure 16 Per Channel Data Rate (bps) for Hub/Spoke Cases

Processing Load Factor (PLF) Crossover Plots

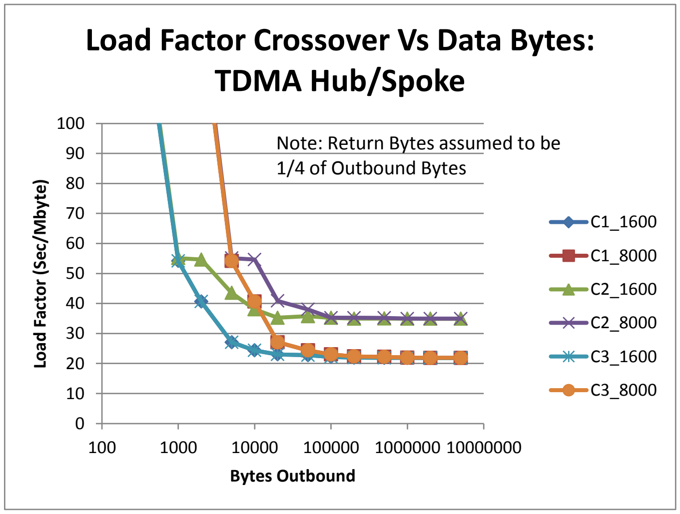

Figure 17 **PLF Crossover for TDMA Hub/Spoke Cases**

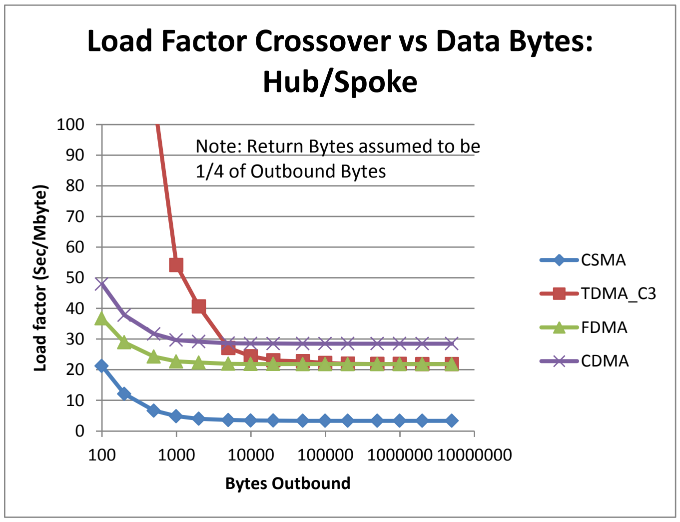

Figure 18 **PLF Crossover vs MAC Protocol**

B. Round Robin Topology Cases

Cases 6-10 are Round Robin Cases. It is assumed that they are at satellite distances and speeds, and that they use highly directional antennas (so there is no for need time division multiplexing). Time Division Duplexing and

Frequency Division Duplexing are considered. The CDMA option selected here assumes a spreading factor of 8 vs the spreading factor of 64 used for the Hub/Spoke cases. The Signal to Noise ratio is assumed to be the same as with the Hub/Spoke cases, which results in higher data rates, given the fact that frequencies can be re-used between adjacent cells. The calculated per channel transmit rates of the various options is shown in Figure **19**. Processing Load Factor Crossovers are shown in Figure **20**.

Round Robin	Case 6	Case 7	Case 8	Case 9	Case 10
CDMA_8	2,773,559				2,773,559
FDMA	11,419,600		5,655,573	11,419,600	
TDMA_1600		11,419,600			
TDMA 8000		11,419,600			
CSMA		22,947,653			

Figure 19 **Data Rates for Round Robin Topology Cases**

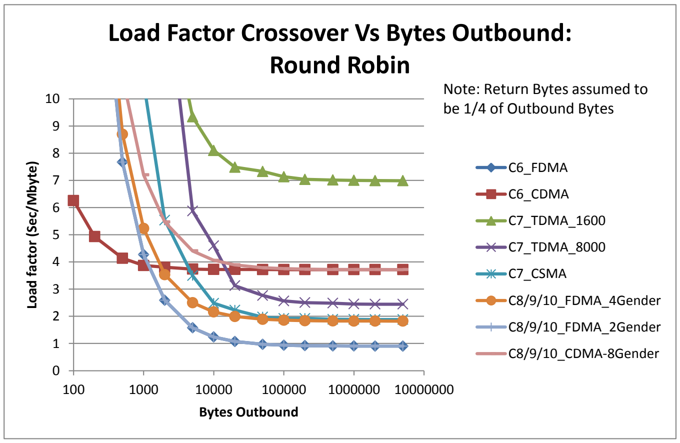

Figure 20 **PLF Crossover for Round Robin (2)**

V. Analysis

The Processing Load Factor Crossover graphs in Figure **17**, Figure **18**, and Figure **20** provide us with a mechanism to compare MAC protocols from the perspective of efficiency. Two separate factors can be represented by these graphs. The first is the size of the problem as represented by the amount of raw that needs to be distributed, (Bytes Outbound axis). The second is the size of the problem from the perspective of processing power, which is represented indirectly by the Processing Load Factor axis. The representation is indirect because the axis represents the time it takes to process a given amount of raw data (lower implies a faster processor).

When the processing capacity of the system is above the line, the system is processor bound (i.e. process time exceeds transport time). When the processing capacity of the system is below the line, the system is transport bound (i.e. transport time exceeds process time). Comparing curves can be simplified by considering the knee of the curve and the curve's asymptote independently. The knee of the curve shows how much the efficiency of the WDC application is affected by MAC protocol overhead that is sensitive to the size of transport driven processes. The asymptote provides a best case indication of efficiency of the protocol.

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There are two ways that these plots can be interpreted. One is that given the RF system bandwidth and a MAC protocol, the Processing Load Factor Crossover plot represents the fastest processor that can be exploited by the system for a given size of raw data distribution. A second interpretation is that given a particular type of problem to be addressed, with a given processing complexity (i.e. Processing Load Factor) and a given amount of data that needs to be distributed (Bytes outbound), whether the curve lies above or below that point determines whether the application will be transport bound.

1) *Metrics*

One observation from this analysis is that link data rate does not make an effective metric for Wireless Distributed Computing applications. This can be seen in the processing Load Factor Crossover plots where the size of the transport problem can have a significant impact on whether the system is transport bound or processor bound.

As was highlighted in the detailed analysis, the nature of the MAC protocol in a particular environment (e.g. Hub/Spoke at close range) can lead to resource contention that reduces the efficiency of the system. The Processing Load Factor Crossover plot provides a good mechanism to interpret efficiency of the protocol. Its value is that it is independent of the protocol being examined, and can be related directly to the size of the distributed computing problem in two dimensions (processing load and transport load).

2) *Analysis of Plots*

What we see from Figure **17** is the comparison of the TDMA cases. Two factors are illustrated: size of the TDMA slot, and the use case. Cases C1 and C3 are generally more efficient than case C2. The difference for Case C2 is that it separates transmit and receive frequencies (i.e. it is FDD vs TDD). Why this is significant is that the assumptions of the processing model were that more raw data had to be distributed than processed data returned. However, when the MAC protocol was created, bandwidth was allocated equally between transmit and receive processes. Since the definition of the Processing Load Factor Crossover point is the point at which the time spent processing data is the same as the time spent transmitting processed data (or receiving raw data), it was not possible for the time spent processing to be simultaneously equal to the time spent transmitting and the time spent receiving. An unequal distribution of bandwidth between transmit and receive processes would have improved efficiency.

A second observation that can be drawn from these plots is that the 8000 byte slot is more efficient than the 1600 byte slot. In other words, there are more opportunities for inefficiency in a 1600 byte slot than in an 8000 byte slot. Some of those inefficiencies (such as 5X more guard time between slots) never go away. The difference in slot size also has a significant impact on the knee of the curve. Put simply, until the slot size is larger than the amount of data transmitted there will be unavoidable inefficiencies. The 1600 byte and 8000 byte thresholds can be clearly seen in the plot.

What we can see from Figure **18** is the non-TDMA cases for the Hub/Spoke case. The C3 case from the TDMA cases is illustrated on these plots to provide a comparison point. Of note on this plot is that both TDMA and FDMA converge to the same minimum. FDMA, since it does not have to deal with the question of an unfilled slot does much better with smaller problem sizes. CSMA shows as a much better option (for these specific conditions), and CDMA a slightly less desirable option. One point of interest for the CDMA case is the choice of spreading factor. A spreading factor of 64 was chosen for a problem with only 7 nodes. Had the actual number of nodes been 16, both the TDMA and the FDMA cases would have produced plots that were about twice as high (since data rates would be about half). The CDMA case, however, would have remained at or near the same level, so it could be a better selection for some cases. To see the impact, CDMA was revisited in the Round Robin cases, but with a spreading factor of only 8.

What we see from Figure **20** is the Processing Load Factor Crossover for the Round Robin topology. One difference in assumption here is that the CDMA system is illustrated with a spreading factor of 8. It achieves the same asymptote as the 8-gender FDMA system. The two TDMA systems (1600 byte slot and 8000 byte slot) straddle the 8-gender system. The 4-gender FDMA system and CSMA achieve the same asymptote, and the 2-gender FDMA system achieves the lowest asymptote.

VI. CONCLUSIONS

This paper has taken a look at the impact of Media Access Control protocol on Wireless Distributed Computing (WDC) Applications. It was found that choice of MAC protocol, along with topology, can have a significant impact on WDC efficiency, and a metric to illustrate protocol differences was found that is sensitive to both the processing load of the WDC application, and the data transport load. The metric allows evaluation of efficiency both from the perspective of the size of the WDC problem form a processing load perspective and a raw data size perspective. The metric shows that the four broad classes of MAC protocols are all inefficient at small transport data sizes and have a knee to their curves.

From an intuitive perspective, the performance issue with MAC protocols appears to relate to inefficiencies in channel usage, and channel contention. One conclusion that can be drawn from this analysis is that while contention for RF resources is an enemy to WDC applications, the impact of distance is much smaller, even when its impact on guard bands or guard times is considered. Distance may still a problem for forming the wireless network itself but the distributed computing application that rides over the network can still enjoy high data rates and simple strategies for pipelining transported data. This suggests that adding WDC applications to long distance / high data rate systems might be as productive, or more productive, than adding WDC to densely packed wireless mesh networks.

VII. APPENDIX

A. Acronyms

ACK	Acknowledgement
CDMA	Code Division Multiple Access
CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
FDMA	Frequency Division Multiple Access
MAC	Media Access Control
PLF	Processing Load Factor
RTS	Request to Send
Rx	Receive
TDMA	Time Division Multiple Access
Tx	Transmit
WDC	Wireless Distributed Computing

VIII. REFERENCES

1. Charan Langton, “Intuitive Guide to Principles of Communication – Code Division Multiple Access”, 2002, www.complextoreal.com
2. John Farserotu, Ramjee Prasad, “ IP/ATM Mobile Satellite Networks” Artech House Universal Personal Communications Series
3. “Spectrum Efficiency of CDMA-PAMR and Other Wideband Systems for PMR/PAMR”, ECC with European CEPT.
4. “Guardbands and the Frequency Separations at the Duplex Transition Required for Deployment of CDMA-PAMR” ECC Report 38
5. Dinesh Datla, Haris I. Volos, S. M. Hasan, Jeffrey H. Reed and Tamal Bose, “Task Allocation and scheduling in wireless dostrobited computing networks” ANALOG INTEGRATED CIRCUITS AND SIGNAL PROCESSING, Volume 69, Numbers 2-3 (2011), 341-353, DOI: 10.1007/s10470-011-9788-1
6. Xuetao Chen Newman, T.R.; Datla, D.; Bose, T.; Reed, J.H. “Cross-layer resource allocation for wireless distributed computing networks” GLOBECOM 2009 - 2009 IEEE Global Telecommunications Conference, p 6 pp., 2009
7. Xuetao Chen; Hasan, S.M.; Bose, T.; Reed, J.H. “The impact of channel variations on wireless distributed computing networks” Proceedings 2010 IEEE Radio and Wireless Symposium (RWS 2010), p 605-8, 2010
8. Janche Sang; Lin, C.-H.M.; Varadaraja, S.; Mu-Cheng Wang “Distributed network computing over wireless links” Proceedings. 1997 International Conference on Parallel and Distributed Systems (Cat. No.97TB100215), p 252-9, 1997
9. Fantacci, R. (Univ. of Florence, Florence, Italy); Tarchi, D.; Tassi, A. “Wireless Communication Protocols for Distributed Computing Environments” Advanced Trends in Wireless Communications, p 399-420, 2011
10. Ruan, Dian-Xu Zhang, Xiao-Guang; Li, Hui; Liu, Yin “The research of optimal algorithm for task scheduling underground wireless network Based on distributed computing” Proceedings - 2010 International Conference on Manufacturing Automation, ICMA 2010, p 151-155, 2010, Proceedings - 2010 International Conference on Manufacturing Automation, ICMA 2010
11. Makoond, B. Khaddaj, S.; Ong, D.C.C.; Oudrhiri, R.; Tunnicliffe, M. “Distributed computing techniques for wireless messaging systems” Journal of Algorithms & Computational Technology, v 2, n 3, p 429-46, Sept. 2008