A Reliable Peer-to-Peer Protocol for Multi-Robot Operating in Mobile Ad-Hoc Wireless Networks

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Abstract: *Cooperative behaviour in multi-robot systems are based on distributed negotiation mechanisms. A set of autonomous robots playing soccer may cooperate in deciding a suitable game strategy or role playing. Degradation in broadcast and multicast services are widely observed due to the lack of reliable broadcast in current IEEE 802.11. A reliable, Peer-To-Peer (P2P), fast auction-based broadcast is proposed for a team of robots playing soccer interconnected using an ad-hoc wireless mobile network. Auction broadcast includes a sequence order to determine the reply order of all nodes. This helps minimizing the potential of Medium Access Control (MAC) conflicts. Repeated back-off are not desired especially at low load. Uncoordinated negotiation lead to multiple outstanding auctions originated by distinct nodes. In this case, the sequence order becomes useless as auction times are interleaved. An adaptive MAC is proposed to dynamically adjust the reply. Protocols are implemented as symmetric multi-threaded software on an experimental Wireless Local Area Network (WLAN) embedded system. Evaluation reports the distribution of auction completion times for peer-to-peer operations for both static and mobile nodes. Protocol trade-offs with respect to auction response time, symmetry and fairness, and power consumption are discussed. Proposed protocols are embedded as a library for multi-robot Cooperative Behaviours (CBs). Evaluation shows the proposed protocol preferences versus the behavioural primitives with specific communication patterns.*

Keywords: *Auction communication, cooperative multi-robot, distributed intelligence, peer-to-peer, wireless protocol.*

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1. Introduction

A multi-robot cooperative architecture is a general framework for implementing distributed artificial intelligent behaviours. Usually a three-level functional architecture [13] consists of a few behaviour layers: organizational, relational, and individual levels. A cooperative behaviour consists of a team of independent robots that cooperate towards achieving a goal while complementing each other and resolving conflicts. The role negotiation [5] leads to dynamic role assignment depending upon change in game state and emerging opportunities. Dynamic task allocation in multi-robot cooperation [6, 12] can be implemented as a distributed negotiation mechanism [3] using auction-based frameworks.

A key tactic for a team of autonomous robot playing soccer is the use of the ball-pass behaviour to increase the chance of making a goal. A kicker robot may use auction-based communication and synchronization model to select the robot which is the best positioned to intercept the ball and mark a goal. A reliable P2P broadcast model is needed in mobile robots playing soccer [11] or a team of rescue robots exploring a building after a disaster [10]. Many applications need a reliable and efficient broadcast at the Medium Access Control (MAC) layer [8]. Current IEEE 802.11 Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) broadcast protocol has no recovery layer on broadcast frames. Consequently, unexpected frame loss may deteriorate the quality of broadcast/multicast services. To develop team-wise coordinated actions, a real-time database which is partially replicated in all soccer team members (RoboCup), containing both local and remote state variables, in a distributed shared memory style [11].

An extension to IEEE 802.11 that supports reliable multicast [14] is proposed based on the use of Negative Acknowledgment (NAK). The proposed MAC protocol is suitable for both infrastructure-based mobile networks as well as ad-hoc mobile networks. A cluster consists of mobile nodes that are within range of each other. UDP based simulation results suggest that the proposed protocol performs better than Leader Based Protocol (LBP) both in terms of data throughput as well as reliability.

A Joint Architecture for Unmanned Systems (JAUS) is proposed based to enable communication and control of air/ground/sea unmanned systems [9]. A hierarchical organization enables nodes and components to communicate through the node manager. Messages that pass outside of a subsystem boundary are routed by the Communicator. However, JAUS does not guarantee message delivery.

Robotics Operating System (ROS) [7] uses a messaging subsystem based on the publish/subscribe model and a service-oriented model. Their message passing interface is generic and different transports are supported including shared memory, Transmission

Control Protocol (TCP), and User Datagram Protocol (UDP). The communication system offered by standard ROS alone cannot guarantee a reliable communication among peers.

A multi-robot system [4] uses a set of heterogeneous robots to help disabled and elderly at home. A centralized server collects, aggregates and processes data from robots. The server transmits control actions to robot manipulators using standard 802.11 protocol. The server also uses cloud services for processing computationally intensive tasks such as Simultaneous Localization and Mapping (SLAM), image processing, and kinematics and path planning. A hybrid range-free WSN based localization system [1] closely integrates hop-count and Received Signal Strength (RSS) methods and is implemented over the ZigBee protocol. The system tackles the problems of inaccuracy, costliness, energy consumption, indoor performance and overcoming the requirement of positioning hardware.

In this paper we present an experimental performance analysis of light weight, reliable, peer-to-peer protocols for Ad-Hoc Mobile Wireless Networks (AMWN). Four application-layer auction-based protocols which are based on customized TCP, UDP, UDP broadcast with token passing, and UDP customized broadcast. Experimental evaluation is carried out whereas each protocol is analysed with respect its responsiveness, reliability, robustness under mobility, and fairness.

This paper is organized as follows. In section 2 the cooperative behaviours are presented. In section 3 the P2P auction protocols are presented. In section 4 an adaptive MAC control is presented. In section 5 the performance evaluation and comparison to others are presented. We conclude in section 6.

2. Cooperative Behaviour Using Auctions

Typical Cooperative Behaviour (CB) can be found in a team of autonomous robots that determine their own behaviour based on partial information collected by sensing the environment supplemented with information received from their team-mates. The sense-think-act is an autonomous behaviour based on own sensing like searching-ball, walking-to-ball, stand-behind-ball, kick-ball, etc., Typical CB components are:

1. Game strategy.
2. Role playing.
3. Commitment.

Components are based upon intensive dynamic communication schemes with information interchange among team members.

The game strategy allows tuning to a more or less offensive or defensive strategy in response to some emerging conditions. Role playing re-assigns robot roles (behaviours) to adapt the team to current team strategy and game state using inter-robot negotiations. Examples of role playing: Cooperative Positioning (CP), Role Negotiation (RN), Goal Clearance (GC), Striker-Defender (SD), etc., CP re-assigns roles based on current position of robot, ball, own team, and opponents team. RN coordinate the analysis of game state and collectively determines whether the team should defend or attack as function of remaining time and goal difference, and assignment of new roles. GC coordinates moving the goally which is closer to the ball than any other team mate to kick it towards some partner. SD assigns the robot which closest to ball as a striker and the others as defenders after examining the distance to ball and the position of opponent team as seen by the own team-mates.

Examples of temporary commitments are the Dribbling (D) and Ball-Passing (BP) behaviours. The dribbling allows an attacker to dribble the ball while coordinating its movement with a supporter robot in preparation for kicking or ball passing.

Cooperative behaviours can be implemented over a P2P communication protocol as an auction-based framework for mobile robots forming an Ad-Hoc wireless network. In the next section we present four application-layer auction-based protocols.

3. P2P Auction Protocols

In this section we experimentally assess four auction schemes which are:

1. The TCP P2P (TP) Scheme: the auctioneer communicates with each node that it wants to include in the auction using a separate TCP connection. The auction request and reply are performed using two TCP packets.
2. The UDP P2P (UP) Scheme: the auctioneer uses one-to-one UDP packets to transmit its auction to each participating node. The packet contains destination node IP, IP of the source node and the auction resource ID. The auctioneer implements its auction in a sequential manner, i.e., the first node is contacted first through a UDP packet and after it has responded through a UDP reply, the auctioneer contacts the next node. If a node does not respond, the auctioneer take-up that node and moves to the next node after attempting a fixed Number (N) of retries, in which case the auction is marked with fail.
3. The UDP P2P Broadcast with Token Passing (UPBT) scheme. The auctioneer broadcasts a UDP packet to all the participating nodes. The packet includes a randomly generated time sequence which defines the order in which recipients should return their Acknowledgement (Ack). The received sequence allow determine the order s(i) and start a timer for the duration s(i)*Tack, where Tack is the time for Ack. The i^{th} node transmits:

1. An Ack to the auctioneer with some bidding data.
2. a token to the next node.

Similarly, all remaining nodes reply to the auction and forward their token. The auctioneer concludes the auction if it receives replies from all nodes, otherwise the auction is re-broadcast after including the IDs of the nodes which have not replied in the previous round. The process is repeated until all nodes responded or a maximum of N retries is reached, in which case the auction is marked with fail.

4. The UDP P2P Broadcast (UPB) scheme. UPB is similar to UPBT except that the ith node transmits its Ack to the auctioneer after a silent period of s(i)*Tack with no token send to the next node in the sequence. Adapting the auction protocol to the above two extremes is presented in the next subsection.

4. Adaptive Medium Access Control

A transition from one state to another requires some auction communication be spreads over a relatively large interval of time. Thus, Auction Locality (AL) can be used as an indicator to tune the value of Tack so that to minimize overall auction time through a better coordination of the medium access times. Given the multi-threaded implementation of our algorithm, Tack must be controlled within a range of (TS, Tmax=TS+ Tref) for proper operation of various threads, where TS is a minimal software time to ensure proper operations of the multithread implementation and Tref is the protocol time to transmit the acknowledgment by all the nodes without medium access conflicts.

In the case of Light Auction Load (LAL), the practical value of TACK must be around Tmax, which helps spreading the ACKs on the time axis to avoid potential conflicts. In this case, the time (Tauc) for one round auction transmission and acknowledgment by N peer nodes is calculated according to Equation (1).

$$Tauc = TS + tauc + N\,(TS + Tref + Tguard) \quad (1)$$

Where tauc the protocol time to broadcast an auction without medium access conflicts, and Tguard is a guard time between two successive acknowledgements. Note that sequencing of the Acks is useful only when there is no or little intervening auctions or acknowledgements during the processing of a given pending auction. Node sequencing does not contribute in reducing the potential collisions when the auction time is interleaved with transmissions of other auctions or other ACKs. Specifically in medium to high auction load we need to set up Tack to its minimal value Tmin= TS. In this case the node which received the auction transmits its Ack immediately which leads to busy medium and the activation of the standard back-off mechanism. Each node maintains in a local variable V which hold the most updated value of Tack. V is always within the range of [TS, Tmax]. A Sequence Number (SN) is used as a time stamp to differentiate the aging of transmitted values of V. SN helps select the most recent value of V. Each node has two local variables V and its corresponding SN.

This allows adapting and updating the values of V based on its own measurements, information received from other nodes through the auction broadcast, or the auction acknowledgements. The measurement, update, and propagation of the above local variables (SN and V) is done by each node according to the following three rules:

Measurement: on conclusion of an auction by auctioneer N, the following steps are used to update the local values of V and SN:

- An estimate (T) of the acknowledgement time is evaluated as T=(Tauc-TS-tauc)/N-Tref-Tguard, where Tauc is the overall auction time measured by the timer,
- Update V: V=ATref+TS, where A=(u/max{T/Tref, u}), where u is slightly above 1.

Update SN: SN is updated to the largest among its own SN and the received sequence numbers from the peers through the acknowledgements plus one, SN= $Max_k\{SN_k$:sent by kth peer or own}+1.

Spreading: send current values of (SN, V) with the transmission of:

1. Its own auction.
2. ACK in response to each auction originated by peer nodes.

Update: a node receives (SN, V) with:

1. A new auction originated by some peer node.
2. ACKs in response to its own auction.

The local values of (SN, V) are updated to the most recent pair of values among its previous values and the newly received values.

Note that spreading of the recent values can be done without additional communication other than the standard auction primitives.

5. Evaluation

A stargate embedded system consists of a set of seven single board computers, each is an Intel 32-bit 400 MHz XScale processor and 96 MB Synchronous Dynamic Random Access Memory (SDRAM) and an Ambicom IEEE 802.11 wireless card. Linux OS with drivers for all peripherals and Java Runtime Environment (JRE) are used. TP, UP, UPBT, and UPB protocols were coded in JAVA. Each protocol is experimented until each node completes a total of N auctions. The probability a node to broadcast an Auction is 0.1. The minimum waiting time for a node to return an Ack to the sender is Tref=5 ms and the best estimate for TS is 0.35 ms to account for the software delays due to multi-traded implementation. A 50 m2 experimental area is used.

5.1. Overall Protocol Performance

Table 1 shows the typical performance achieved by each protocol in terms of average auction time for N= 103, the range of time covering 90% of the cases, standard deviation, and average power consumption.

Table 1. Summary of experimental data of four P2P protocols.

Protocol	Average Auction Time (ms)	Range of Auction Time (ms)	Standard Deviation	Power/auction (mW)
TP	180	157-208	42	38.3
UP	61	44 - 135	31.3	23.4
UPBT	57	44-87	17.1	12
UPB	52	44-82	15.2	10.9

For TP, the cost of having reliable communication is offset by the large and scattered completion times which may extend beyond 200 ms. On the other hand the weak reliability of UP is reflected by a linear increase of auction times versus number of nodes. Both UPBT and UPB have close performance as manifested by their respective average, range of auction times, and associated standard deviation. We will focus our experimental analysis on UPB.

5.2. UPB Symmetry, Fairness and Reliability

The histogram distribution of completion times of first four nodes for UPB is shown on Figure 1 (nodes 1-4) and similar plot for nodes 5-7, for which each of the seven nodes completed 103 auctions. The auction time percentage of cases is reported versus the accomplished auction times. The above figures focus on the range of 40 to 70 ms.

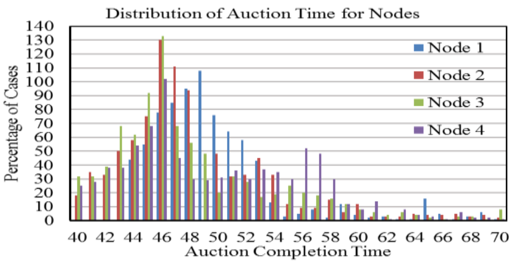

Figure 1. Distribution of auction completion times for nodes 1-4.

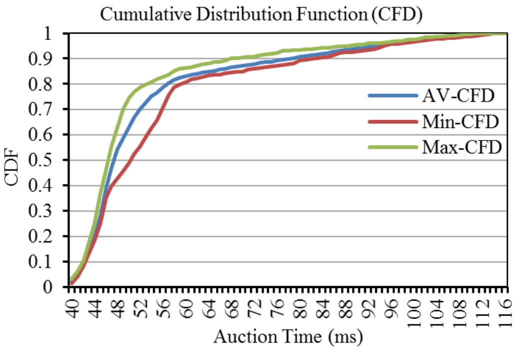

Figure 2. CDF of aggregate auction times of nodes for UPB.

The Cumulative Distribution Function (CDF) of aggregate auction times of all the nodes for UPB is shown on Figure 2. It is clear that 70%, 80%, and 90% of the Auctions are completed in no more than 52, 58, and 81 ms, respectively. The remaining 10% of the auction completion times are scattered within the range of 81-119 ms. The auction times deviate by no more than 15% from the aggregate CDF from average time.

UPB protocol exhibits an acceptable symmetry in auction times and fairness in accessing the medium. The features of UPBT are quite similar to that of UPB with some increase of 5.4 ms in the average auction times. Figure 3 shows the percentage of auctions completed in one single round, two rounds, and three rounds. All experienced auctions among 7 nodes have been completed using only three auctioning rounds, whereas a large majority of nodes responded to the auctioneer in the first round (78%), second round (15%), and third round (7%), respectively.

5.3. Analysis of the Impact of Node Mobility

The impact of location and node mobility are studied in a corridor which is 3m wide and 100m long. Three scenarios are considered:

1. Static nodes.
2. Nodes 2 and 7 are mobile.
3. Only nodes 2, 3, and 7 are mobile.

Each mobile node moves at random in the experimental area at a speed of 0.5 m/s.

Figure 4 shows the CDF for the aggregate auction times of the seven nodes under each of the three studied scenarios. The degradation leads to shift to the right the CDF, which increases with the degree of node mobility. The degradation is due to change in the experimental environment and the node mobility as some nodes are moving which affect the MAC performance, i.e., changes in the interference level and the implied medium access conflicts.

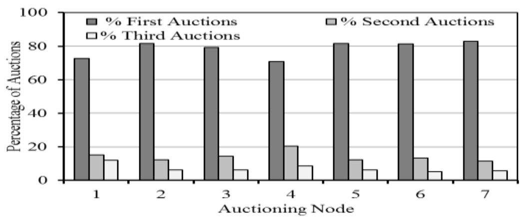

Figure 3. Percentage of cases using one, two, and three rounds.

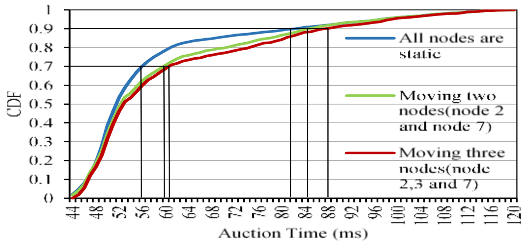

Figure 4. CDF's of Auction times for three mobility scenarios.

Figure 5 shows the percentage of auctions completed in the first, second, or third round by all the nodes in the above three scenarios. Three rounds are still needed for a reliable UPB, i.e., make sure that all the nodes of the Ad-hoc network have successfully replied back. Although, when two nodes or three nodes are moving, the average auction time has been marginally increased, which indicates that the protocol is resilient versus node mobility as the main histogram features of all nodes distribution are preserved.

5.4. Evaluation under Cooperative Behaviours

In this section we experimentally evaluate the proposed auction protocols in implementing Cooperative Behaviours (CBs) with different communication patterns. We implemented nine Customized Auctions (CAs) on the top of proposed auction protocol, which are:

1. Req-Info: Informing agents of events or responses such as alerting own team about game status.
2. Req-Ana: request for geometric data between the robots and the ball.
3. Req-Com: request for help or temporary commitment among a few peers (ball passing).
4. Prep-action: agree on course of action such as the readiness for some coordinated actions.
5. Action: start joining new assigned positions and activation of agents (behaviour).
6. Ball-Control: negotiate assignment of new roles based on claiming ball control by peers.
7. Res-Conflicts: smooth out information inconsistencies using voting.
8. Exception: play with substitute robots or play with a fewer players using prioritized roles.
9. Synch: auction to synchronize coordinated motion.

Table 2. Mapping of cooperative behaviours RN, GC, SD, BP, and D to customized auction library.

	Role Playing			Commitment	
Auctions	**RN Multiple broadcasts**	**GC Scattered multiple collective**	**SD Intensive Multiple collective**	**BP Intensive collective one-to-one**	**D Intensive collective multicast**
Req-Info	3^+	1^+	2^+	1^+	1^+
Req-Ana	3^+	1^+	3^+	1^+	2^+
Req-Com	0	0	0	1^+	2^+
Prep-act	3^-	1^+	2^+	2^-	1^*
Action	0	3^-	0	2^-	1^*
Ball-Contr	2^+	1^-	2^-	3^-	1^-
Res-Conf	3^*	2^*	1^*	2^-	1^*
Exception	1^-	1^-	1^-	1^-	1^-
Synch	0	1^+	0	4^-	3^*
Total	15	11	11	17	13

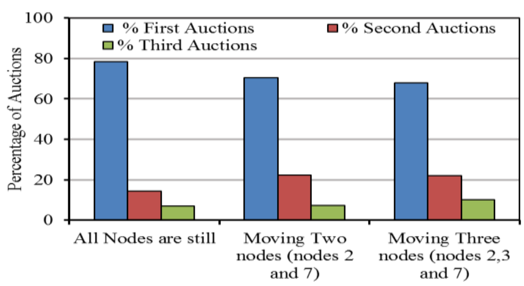

Figure 5. Percentage of cases auction completed using one round, two rounds, and three rounds for three scenarios.

5.4.1. Auction-Based Cooperative Behaviours

We used a set of five cooperative behaviours CBs which have been introduced in Section 3. These are

1. Role-negotiation RN.
2. Goal-clearance GC.
3. Striker-defender SD.
4. Ball-passing BP.
5. Dribbling D.

Below we describe their main body and implied communication pattern.

Role-Negotiation (RN) consists of spreading some global believes like game state and game remaining time. RN consists of multiple outstanding auction broadcasts in a relatively short period of time. Goal-Clearance (GC) allows coordinating the movement of the goalie to the ball and kick it. GC consists of scattered collective communications. In Striker-Defender (SD) the attacker which is the closest to the ball is assigned as a striker and the other peers serve as helpers. SD consists of intensive collective communications. In Ball-Passing (BP) an attacker consults with its own team to find a better placed peer. BP consists of intensive collective communication.

In dribbling (D) an attacker decides to dribble the ball after setting a temporary commitment with a few peers. D consists of intensive collective communication.

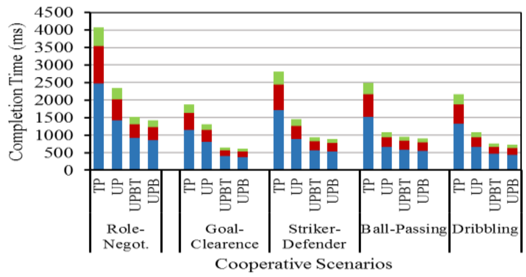

Figure 6. Distribution of completion times of CBs with break for 70% (blue), 85% (red) and 95% (green).

Table 2 shows the mapping of cooperative behaviour RN, GC, SD, BP, and D to the components of the CA auction library. The data shows the average number of auctions that were transmitted by all team mates during the CB phases. A transmission can be a broadcast (+), a multicast (*), or a one-to-one (-).

5.4.2. Experimental Evaluation

Two soccer teams T1 and T2 are used where each team consists of seven players, of which three are attackers, three are defenders, and one goalie. Each CA is implemented on the top of one of the proposed auction protocols. This leads to the execution of a sequence of auctions with its communication pattern (Table 4). Since our objective is to access the quality of communication within the CBs, knowledge about ball, team mates, opponents, and goal is done by simulating the motion by the player module. Ball motion is simulated by a player, which was last to act on it, which also broadcasts its ball position until stop. When a player moves it regularly updates the other players because no vision is assumed.

Figure 6 shows the distribution of completion times for the five cooperative behaviours (RN, GC, SD, BP, and D). The plots show only the CB communication times without accounting for the delay caused by the motion of peers. For example, using TP, UP, UPBT and UPB protocols, behaviour RN completes in 4s, 2.32s, 1.5s, and 1.47s, respectively. Figure 7 shows the distribution of the number of UDPs exchanged, which is considered as an indication of the power consumption. Table 3 reports the average auction time and the rate of packet transmission for each CB for each of TP, UP, UPBT and UPB protocols. Table 4 reports the average auction times and packet rates for TCP, UP, UPBT, and UPB.

For RN, multiple peers produce Multiple Outstanding Auctions (MOA) which is an indication of high auction load. In this case the protocol adaptation forces the nodes to send their Acks without sequencing. The MIS streams are interleaved in time which causes significant increase in auction time. However, the overall Multi Input Stream (MIS) time is quite reasonable, which is evidenced by the large number of packet transmitted, i.e., the network utilization is quite acceptable compared to the other protocols.

Table 3. Performance of the five experimented CBs.

Protocol	Average Auction Time (ms)	Range of Auction Time (ms)	Standard Deviation	Power/auction (mW)
TPTP	180	157-208	42	38.3
UP	61	44 - 135	21.3	13.4
UPBT	57	44-87	17.1	12
UPB	52	44-82	15.2	10.9

Table 4. Average auction times and packet rates (TCP, UP, UPBT, and UPB) for the five experimented CBs.

	Role Playing			Commitment	
Protocol time and packets	**RN Intensive multiple broadcasts**	**GC Scattered multiple collective**	**SD Intensive multiple collective**	**BP Intensive collective one-to-one**	**D Intensive collective multicast**
Average auction time (ms)	180, 84, 83, 79	180, 72, 54, 57	180, 79, 72, 69	1+	1+
Achieved packet rate (p/s)	5.2, 15.7, 35.6, 42.4	5.2, 7.2, 12.4, 12.8	5.2, 12.7, 24.6, 28.2	1+	2+

In GC, nodes carry out fast changes from Broadcast/Multicast (BM) to one-to-one and these transactions are scattered in time due to the goalie motion. Sequencing the ACK transmissions results in a minimal auction times and lower the packet transmission rate. UPBT has shorter auction times than UPB.

In SD, the communication pattern is similar to RN but with a mixture of collective transmissions. BP is featured an intensive collective communication with one-to-one dominance. UP is quite comparable to UPBT and UPB which seems to be equally affected by the busy medium.

D features an intensive collective communication with multicast dominance. There is a clear advantage in favour of UPB over all the other protocols.

UPBT and UPB achieved almost equal response time with some advantage to UPB. UPBT and UPB are between 15% to 60% faster that UP but at the cost of increasing their power consumption by 10% to 18%.

5.4.3. Comparison to Other Contributions

The Reliable Multicast (RM) proposed in [9] using NAKs operates as an extension to IEEE 802.11. Although the simulation results show that RM performs better than LBP both in terms of data throughput as well as reliability. Although, only 0.1% of data packets are undelivered, RM and LBP lose up to twice as many data packets. It is noticed that the reliability of our proposed protocol is higher due to the multiple round broadcast.

The Round Robin Acknowledge and Retransmit protocol [15] has been proposed to improve the reliability of IEEE 802.11 broadcast mechanism.

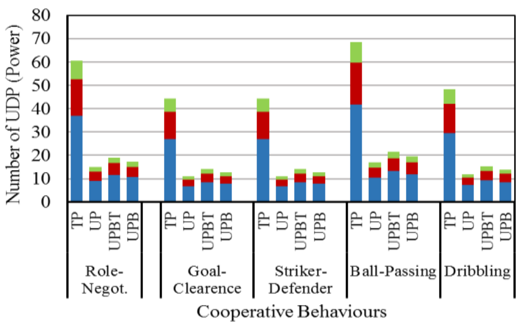

Figure 7. Distribution of the number of UDPs in five CBs with break for 70% (blue), 85% (red), and 95% (green).

It is reported that a simulation has been conducted for a network of 50 nodes within the range of 250 m. The packet delivery ratio is about 90% which is much higher than that of 802.11, which is only 50%. While comparing this protocol with our proposed protocol, our proposed protocol's packet delivery ratio is higher than 90% of the above protocol.

In [2] an auction based communication model is evaluated using:

1. TCP Point to Point Scheme.
2. UDP Point to Point (UPTP) Scheme.
3. UDP Broadcast and Token Passing (UBTP) scheme.

All the above techniques are not purely P2P. The auction is always performed by a head node. The evaluation shows that UBTP scheme takes the least time of 37 ms to communicate with all the nodes. TCP point-to-point scheme takes about 180 ms and UPTP scheme takes 45 ms. The proposed token passing protocol takes only 57 ms which is slightly higher than the other UDP techniques since our proposed technique is purely P2P scheme.

6. Conclusions

Multi-robot cooperative behaviour can be implemented as auction-based distributed negotiation mechanisms is useful for a team of robot playing soccer. Current IEEE 802.11 lacks a reliable broadcast and multicast services. A reliable Peer-to-Peer auction-based protocol is proposed and experimentally evaluated. We proposed an adaptation mechanism to improve the protocol response. In the evaluation, we presented the distribution of auction times for assessing the response time and reliability. The general observations for indoor operations are:

1. Symmetric code in all nodes.
2. Response times are alike for all nodes.
3. Acceptable level of reliability.
4. Low power consumption.

Proposed protocol is embedded as a library of collective communications and experimentally evaluated using a set multi-robot cooperative behaviours. Evaluation shows protocol preferences versus the primitives with communication patterns.

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