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The Use of Clustered Wireless Multihop Networks in Industrial Settings

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Abstract

This paper suggests a cluster collision avoidance mechanism and a dual transceiver architecture to be used in a clustered wireless multihop network. These two contributions make the clustered wireless multihop network the preferred architecture for future industrial wireless networks. The wireless multihop cluster consists of one master and several slaves, where some of the slaves will act as gateways between different clusters. Frequency hopping spread spectrum is used on a cluster level and to avoid frequency collisions between clusters a "neighbor cluster collision avoidance mechanism" is proposed and evaluated through simulations. To break up the dependence between the clusters, introduced by the gateway nodes, each node is equipped with two transceivers. The paper is concluded with a suggestion to use a clustered wireless multihop network with orthogonal hopping sequences for an industrial setting.

1. Introduction

Industrial networks have traditionally used wired communication between sensors, actuators and programmable logical controllers (PLC). However, the rapid development and deployment of wireless communication during the last decade has increased the interest to use wireless access within the industry as well. The wireless multihop topology has been predicted as a future evolution for industrial communication systems [1] - [5]. The wireless multihop network is built up of autonomous wireless stations without any fixed infrastructure or centralized control (e.g., access points or base stations). The network is self-organizing and all control mechanisms are distributed. The multihop topology represents a more flexible architecture than a network with a fixed infrastructure and it has the ability to cover a reasonably large area, such as a factory, using multihop peer-to-peer communication. The flexibility and the decentralized autonomous topology make the wireless multihop architecture a very attractive candidate for, e.g., temporary product lines and diagnostics.

In this paper, a clustered wireless multihop topology is considered meaning that all the nodes are divided into subsets [6] according to some parameter such as space, Fig. 1. Every cluster contains a master regulating the traffic within the cluster and the members of the cluster are called slaves. To provide the multihop capability gateway nodes must be placed on the border between the different clusters. The clustered multihop architecture can today be found in *wired* industrial networks, e.g., P-NET. However, the clustering of nodes in an industrial setting is usually not based on the spatial location of nodes, but instead it is based on process affiliation. This implies that if clusters are going to be used in a wireless network, the clusters could be situated on top of each other. This introduces added requirements on avoiding interference and collisions between clusters.

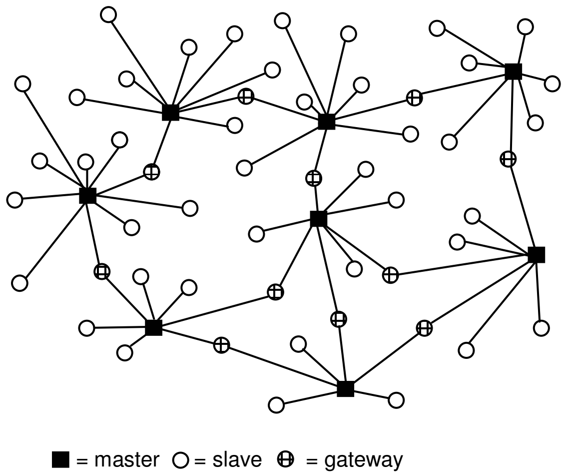

Figure 1. The clustered multihop network, containing masters, slaves and gateways.

The wireless feature itself implies three immediate benefits. It reduces the number of wires. This was one of the main driving forces behind the development of field bus systems [7], where multiple signals to/from sensors, actuators, field controllers and human interfaces were multiplexed on the same wire instead of using a single wire for each individual signal. Further, motions, vibrations, heat variations and aggressive substances put mechanical and chemical stress on wires which eventually

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break [8], or even worse, introduce transient and intermittent signal errors [9].

The wireless network also results in increased mobility and a new dimension of freedom for operators and service personnel [2] since the human interface can be portable. The increased flexibility implied by the decentralized topology enables autonomous guided vehicles [10] and handheld terminals [11] to communicate directly with the surrounding machines rather than communicating via an access point that is connected to a wired backbone. The wireless multihop network may even be used during the product assembly sequence, performing diagnostic tests or downloading software [12]. Industries that often need to reorganize their production lines have much to gain from using wireless multihop networks in order to satisfy demands on "just in time" production [11].

Finally, the wireless multihop network topology actually provides an inherent fault tolerance mechanism. Redundant information paths between source and destination can be established for safety critical communications. The distributed architecture enables cooperative operations where several neighboring stations work together to achieve reliable communications.

All these benefits suggest the use of wireless multihop networks in factory communications systems. However, the use of wireless communication in factory settings has been pointed out several times in the literature as being hard to accomplish [8, 12, 13] and the main issue often referred to is that the wireless medium is error prone [14]. The higher error probability could be combat by using the inherent fault tolerance provided by the multihop topology and by using a robust channel coding strategy. In a wireless multihop network, some nodes easily become bottlenecks due to the fact that it can be hard to control the traffic pattern. Deterministic orchestration of control functionality, such as medium access control, in a spatially distributed network is a difficult task to accomplish. The overhead introduced by the medium access control and the routing information exchange is large, especially if the units are highly mobile and the network topology is changing rapidly.

Wireless multihop networks have been considered for a wide range of applications and standards. They were initially thought of as tactical combat radio systems [15] and later on used in the amateur radio society [16] creating large packet radio networks. Lately, it has been used for providing wireless internet access in so-called wireless community networks; a specific example is the freifunk network [17] in Berlin (i.e., a mesh network).

One of the very first wireless short-range communication standards was Bluetooth, which catchphrase was "cable replacement". It is based on the master-slave concept but the network topology is called piconet and each piconet can only contain eight members. In the Bluetooth standard there are means for connecting several piconets into a scatternet enabling multihop by the use of gateways. However, the gateways introduce a state of dependence between the internal medium access schemes of the piconets [18] which is further enhanced by the fact that there is no synchronization between the piconets. These two problems make it hard for a gateway to participate in two or more piconets at the same time. The Bluetooth standard has solved these problems by allowing the gateway to only be active in one piconet at a time.

Several methods have been proposed for solving the inter-cluster scheduling problem [1] and these are often based on rendezvous points [19]. A rendezvous point is a particular time slot when the gateway should be present in a specific cluster, for exchange of data with this cluster's master, i.e., rendezvous points are required for each cluster the gateway is a member of. The global optimal inter-cluster schedule is NP-complete [19]. However, local suboptimal solutions based on random methods can be constructed using rendezvous windows with pseudo-random length [20]. These rendezvous windows are specific time frames allocated by each master that the gateway node is associated with. The time windows are different for each cluster and the masters sharing a common gateway exchange information about their allocated time frame in order to avoid overlap in time. Schemes where these rendezvous points adaptively change to the present traffic pattern has also been proposed [21]. The problem in general with rendezvous point scheduling approaches is the maintenance and the formation of the schedule [1], which introduces traffic overhead and computational complexity. A straight forward solution is the walk in approach [22], where the master simply polls the gateways according to the local cluster's cycle and data exchange can only take place if the gateway is present, i.e., slots will be wasted when a gateway node is not present.

In this paper an architectural solution to the inter-cluster scheduling problem is provided and an enhanced version of Bluetooth's scatternet concept is presented. The paper further discusses and shows through simulation how interference and collisions between clusters can be avoided. Given the contributions of this paper we propose the clustered multihop architecture to be the preferred topology for future wireless industrial networks. The remainder of this paper is organized as follows. First, the clustered wireless multihop network is explained in more detail and continued with a hopping sequence assignment for the frequency hopping spread spectrum system used therein. Next the assignment problem is analyzed through simulations and the paper is concluded with results and a proposal of using a wireless multihop network for an automation network.

2. Clustered wireless multihop network

The clustered wireless multihop network architecture used here is constructed out of masters, slaves and gateways, Fig. 1. Each cluster consists of one master and several slaves where some of the slaves will act as gateway between clusters. All nodes in the network are time synchronized, e.g., by being equipped with a GPS receiver or some other type of receiver that is able to receive broadcasted time marks. Internally inside each cluster the medium access is based on a master-slave scheme, where the master polls each slave to see whether each slave has something to send. This procedure is done in the same time division duplex (TDD) polling manner as in a Bluetooth piconet [23] except that an external global time reference is used and only single slot packets are allowed. The TDD implies that two time slots are used for each transmission: one from master to slave and one from slave to master.

The frequency hopping spread spectrum (FHSS) is used as physical layer. In an FHSS system the total bandwidth is divided into a number of narrower sub-channels and the transmitter is changing frequency channel according to a predetermined hopping sequence. There are different ways of generating the hopping sequence whereas three is discussed in the next section. FHSS was early pointed out as an attractive technology for use in a clustered wireless multihop network architecture [23]. The frequency hopping provides resistance to fading, co-channel interference and hostile jamming [6, 24].

The gateways, which are slaves in two different clusters, introduce dependence between the clusters since they are unable to transmit and receive at the same time. This implies that the single transceiver must be time multiplexed between the adjacent clusters and the time schedule within each cluster will become dependent on each other through the gateway node's presence [18]. This is a problem that is here solved by using two separate transceivers in every node [25], i.e., a dual-radio node. The result is; a gateway node that does not need to switch its presence between the clusters, breaking up the dependence between the clusters' time schedules.

3. Hopping sequence generation in FHSS

In this section three different ways of generating hopping sequences in FHSS is presented; random channel assignment, random channel assignment with neighbor cluster collision avoidance, and orthogonal channel assignment. The random channel assignment with neighbor cluster collision avoidance is used in the simulations in the next section. The hopping sequence assignment problem is NP-complete [26] and practical solutions are either heuristic or random, in the latter case non-orthogonal hopping patterns are applied to clusters in co-channel interference range. When random methods are used, transmission collisions can occur between concurrently operating clusters. This happens when two or more clusters utilize the same frequency channel in the same time slot, i.e., co-channel interference. These collisions must be avoided to an as large extent as possible in order to maximize the overall system capacity of the network.

3.1. Random channel assignment

Bluetooth is a FHSS system using the 2.45 GHz ISM band and it divides the total frequency band into 79 channels, which are 1 MHz wide. The hopping sequence generation is pseudo-random [23] and uses the master's identity together with the master's internal clock. This ensures that the generated sequence is random in its distribution [27], but the actual sequence is predictable if the seed of the generator is known (i.e., the master's identity). All transceivers of a cluster use the same clock and identity and when a node wants to become a member of a piconet (Bluetooth's cluster) it adjusts the identity settings to suit that specific piconet. The resulting hopping pattern is non-orthogonal meaning that collisions can occur between adjacent piconets. Since the local clock is used in Bluetooth there is no synchronization between the different piconets.

3.2. Random channel assignment with neighbor cluster collision avoidance

In this paper a new channel assignment strategy is simulated and applied in a clustered wireless multihop network using FHSS. It is called a random channel assignment with neighbor cluster collision avoidance (NCCA). The goal with this new mechanism is to avoid collisions among clusters and thus reduce the co-channel interference. The NCCA mechanism is also based on the same pseudo-random generator as used in Bluetooth where the master's identity together with the clock is used for generating the hopping sequence and there are 79 different frequency channels available.

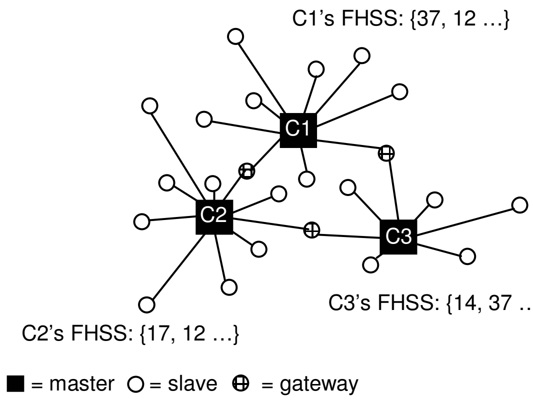

Figure 2. Clusters with information about neighboring clusters' hopping sequences.

However, the big difference from Bluetooth's random channel assignment is that we feed the global clock into the generator enabling us to determine neighboring clusters hopping sequences through the knowledge of the different masters' identities. In Fig. 2, an example with three clusters are shown, where the masters know the neighboring masters' identities through their gateway nodes. The pseudo-random generator is used for both generating the own hopping sequence as well as finding the neighboring clusters' hopping sequences.

The result will be that a time-frequency schedule is set up, see Fig. 3. The same frequency is utilized for both the master-slave request and the slave-master response (in Bluetooth these two operations use different frequencies). From this time-frequency schedule the clusters can see that there will be collisions in the future. The actual avoidance is based on that the cluster with the lowest identity does not perform any transmission when two neighboring clusters intend to utilize the same frequency in the same time slot. This may seem unfair for clusters with low identities, but this problem can be solved by simply interchanging between highest and lowest identity for selection of transmission. This choice can in turn be controlled by a globally known pseudo-random sequence, but this out of the scope of this paper.

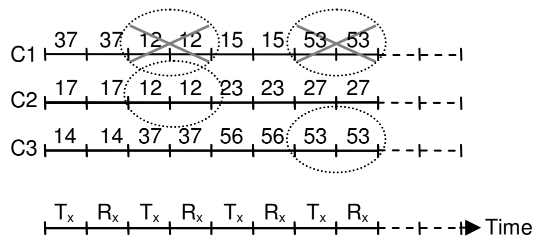

Figure 3. Time-frequency schedule for three clusters.

As an example consider cluster C1, C2 and C3 in Fig. 3. Before starting a transmission, the masters of {C1, C2, C3} calculate the neighboring clusters' next frequency to see if any frequency collision will occur. In clusters where frequency collisions are found, in our case {C1, C2} for timeslot 3 and 4, the cluster with the highest identity is allowed to initiate a transmission and the other cluster must stay idle for these time slots. Then the same happens at frequency channel 53 between C1 and C3 and once again C1 must skip transmitting since C1 has lower identity than C3.

If clusters at two or three hops away were taken into account the co-channel interference would decrease even more, and more collisions could be avoided.

3.3. Orthogonal channel assignment

If the network topology is known in advance and this is often the case with industrial networks an orthogonal channel assignment is possible. Orthogonal sequence generation ensures that there will not be collisions between clusters in co-channel interference. The assignment problem is as previously mentioned a NP-complete problem however there are a lot of available greedy algorithms [26, 28, 29], that give a good sub-optimal solution. The channel assignment problem in a clustered wireless mesh network is similar to frequency [29] or code assignment [26] in cellular networks, i.e. a graph coloring problem.

The pseudo-random hopping sequence generator must be exchanged for a deterministic hopping generator. Since all nodes are assumed to be time slot synchronized it is possible to have 79 orthogonal hopping sequences by time shifting one sequence. The basic hopping sequence is HS_1={1, 2, 3, 4, 5 …. 78, 79} the second is HS_2={79, 1, 2, 3, 4, 5 …. 77, 78}, and so forth until HS_{79}= {2, 3, 4, 5, 6 …. 79, 1}. If all those 79 sequences are shifted synchronously each second time slot, 79 orthogonal channels are available. Furthermore, it is possible to spatially reuse a channel if a cluster utilizing a specific channel is far enough spatially separated from another cluster utilizing the same channel, i.e., outside co-channel interference range.

4. Simulation parameters

A discrete event simulator has been developed and used for the performance evaluation. The simulation assumes a 100 x 100 meter square area. The (X_j, Y_j) position for node j is drawn from uniform distributions [0, X_{max}] and [0, Y_{max}]. The signal-to-interference ratio (*SIR*) [14] is the ratio between the received signal energy P_r and the sum of the energy of all interfering signals, I_i, plus the thermal noise N_0, where index i is defined as *the set of all nodes that transmit concurrently utilizing the same channel*, according to:

$$SIR = \frac{P_r}{N_0 + \sum_{i \in transnodes} I_i} \tag{1}$$

The interference level at a certain point in time and space is a direct consequence of the power used by all concurrently ongoing transmissions and the actual positions of the transmitting nodes. Furthermore, the necessary transmission power is derived from the distance (signal path loss) between the transmitting and the receiving nodes. The average large-scale path loss, L_p, for an arbitrary transmitter-receiver separation is a function of the distance r and the path-loss rate exponent n [14]:

$$L_p(r,n) = L_f(r_0) + 10n\log_{10}\left(\frac{r}{r_0}\right) \tag{2}$$

where r_0 is a reference distance for the far field. The path loss exponent, *n,* indicates the rate at which the path loss increases with the distance, *r*. It can vary between 2 and 6, where $n = 2$ is free space propagation, $2 \le n \le 4$ is obstruction in factories [10] and $4 < n \le 6$ is obstruction in home/office environments [14]. The r_0 distance should be greater than the near field of the antenna (Fraunhofer distance), approximately equal to one meter in our case. The path loss up to that reference distance, r_0, is either determined from a measurement close to the transmitter antenna or by the free space propagation loss equation according to:

$$L_f(r) = 10\log_{10}\left(\frac{G_t G_r \lambda^2}{4\pi^2 r^2}\right) \tag{3}$$

where G_t and G_r [14] are the antenna gains at the transmitter and receiver, respectively. In a wireless multihop network the antenna gain is preferably unity. The wavelength, λ, is given by the carrier frequency in use. The received power, P_r, [14] can be calculated according to:

$$(P_r)_{dB} = 10\log_{10}(P_t) + L_p(r,n) \tag{4}$$

The interference level, I, has an impact on the necessary transmission power since a certain SIR level is necessary for the receiving node in order to correctly receive the transmission. The interference, I_i, [14] from a concurrently transmitting node, i, using the same frequency, is calculated as:

$$(I_i)_{dB} = 10\log_{10}(P_i) + L_i(r,n) \tag{5}$$

The physical layer uses FHSS and all clusters use master-slave polling. In this simulation, each master polls the slaves in a round-robin fashion; two time slots are used for each node in each round (forward/reverse message exchange). All clusters are further assumed to be operating continuously.

The radio has a maximum output power of 20 dBm, which gives a nominal range of approximately 100 m. We assume transmit power control where the target received signal strength (the RSSI value) is -60 dBm at the receiver. The output power of the transmitter is controlled in steps of 2 dB between -20 dBm and 20 dBm (20 steps). If the received signal strength is below -86 dBm it is considered to be non detectable interference by the receiver. An ordinary Bluetooth transceiver has a sensitivity of approximately -82 dBm at a bit error rate of 10^{-3}. The SIR at the receiver must be above the specified SIR threshold, SIR_{th}. If, $SIR < SIR_{th}$, the reception is counted as a collision and simulations have been conducted for a SIR_{th} of 10 dB and 15 dB.

The formation of the network is done by a clustering process that forms feasible interconnected sub-networks out of the total set of nodes [30]. In our case the lowest-ID algorithm [31] is applied. In this algorithm, the identification number (ID) of the nodes is used to elect the master in a cluster. This algorithm chooses the master on the spatial random distribution of the nodes, their IDs, and does not perform any kind of optimization. The master's ID will become the ID of the cluster.

The lowest-ID algorithm assumes a common broadcast channel; therefore a common control channel is used, formed by a globally known hop sequence. This hopping sequence is formed by simply allocating one address as a control channel address and applying slotted Aloha [32] as medium access on the shared control channel.

5. Simulation results

In this section the NCCA mechanism is evaluated by simulation, using the simulation model described above. First the individual capacity of clusters versus the total number of clusters has been simulated for two different values of the SIR_{th}, 10 dB and 15 dB. The graph in Fig. 4 shows that the NCCA mechanism provides an individual cluster capacity gain compared with the case using only random channel assignment without NCCA. The graph further reveals the positive effect that the receiver resistance against interference, SIR_{th}, has on the performance of individual clusters capacity.

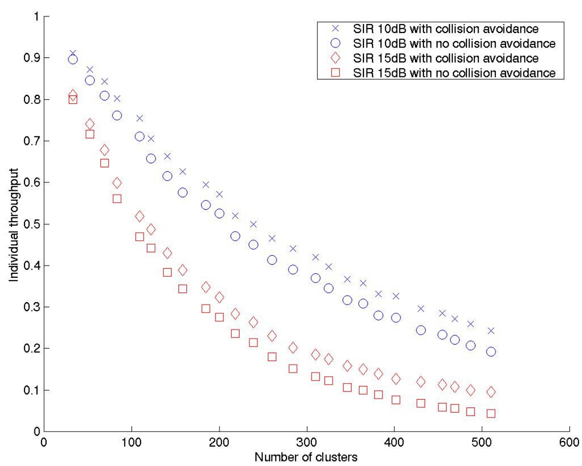

Figure 4. Average throughput per cluster versus the number of clusters. Path loss exponent *n*=2.

The graph in Fig. 5 shows that the increase in aggregated throughput is close to linear for up to 100 coexisting clusters at a SIR_{th} of 15 dB and up to 200 coexisting clusters at a SIR_{th} of 10 dB. The *maximum* aggregated throughput for SIR_{th} = 15 dB is achieved around 175 clusters and a *maximum* for a SIR_{th} of 10 dB is reached around 300 clusters.

The maximum aggregated throughput is a border between the linear stable region and when the system goes unstable. The conclusion is of course that the system should operate in the linear stable region and the ultimate system capacity should settle on a constant value and not go towards zero when the system is overloaded.The simulations show that the NCCA allows the system to operate under higher system load without entering the unstable region. A substantial system capacity gain is available if it is possible to lower the SIR_{th}.

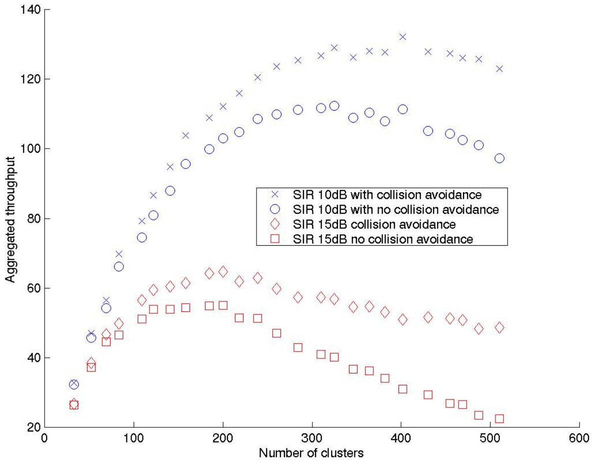

Figure 5. Aggregated throughput versus number of clusters, path loss exponent *n*=2.

The maximum aggregated system capacity curve, upper bound in Fig. 6, shows the ideal achievable performance if no frequency collisions occur at all, i.e., the *optimal* collision avoidance performed by the NCCA when all frequency collisions in co-channel interference are resolved. In that case the aggregated system capacity would increase linearly with the number of clusters (node density).

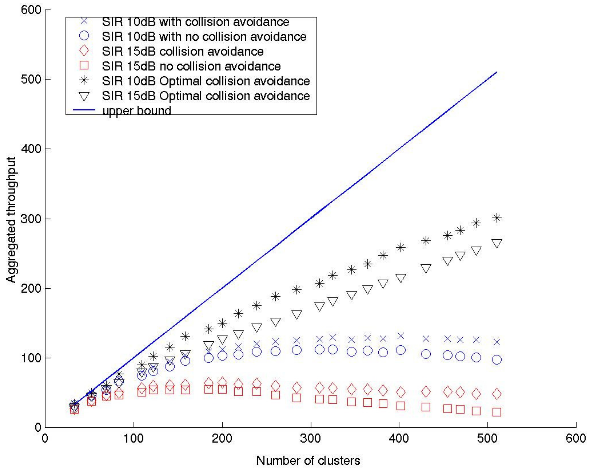

Figure 6. Aggregated throughput versus number of clusters, with the maximum capacity limit plotted and an optimal frequency hit avoidance, *n*=2.

The co-channel interference range is determined by the clusters, utilizing the same frequency, situated up to for example three or four hops away. It should be noted that the optimal NCCA performance is dependent on the cluster density, the path loss and the SIR_{th} of the receiver. These three parameters control the co-channel interference range, which reflects the amount of clusters that have to be considered when avoiding frequency collisions. The *optimal* performance of NCCA could be an indication of how the performance could be when using orthogonal hopping sequences (i.e., no collisions between clusters in co-channel interference).

The plots in Fig. 7 reveal the fact that when the path loss exponent is greater then 2 the aggregated system capacity is increased significantly. The aggregated system capacity is then close to optimal and the system capacity scales linearly with the increase of clusters (node density) up to 500 clusters in 100 x 100 meter area, which is very good. This indicates that very few collisions actually take place in the time-frequency domain, i.e., high path loss provides spatial isolation against co-channel interference.

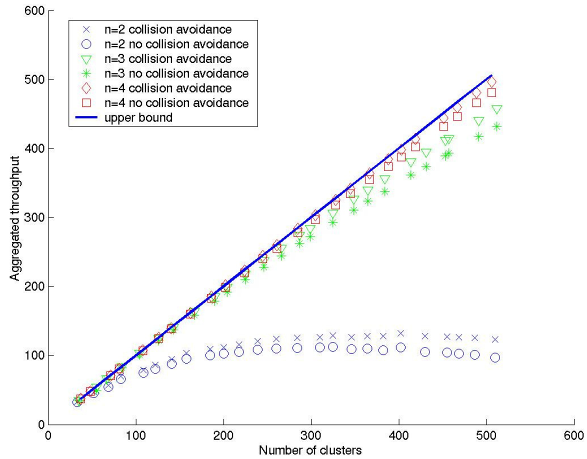

Figure 7. Aggregated throughput for different path loss exponent *n*.

Important to notice is that all curves plotted in Fig. 7 should still reach a maximum at some point and then either start to decay or even out, as a result of all available resources in the time-frequency-space domain being fully utilized. This will occur at some density of nodes since perfect spatial isolation is not possible, caused by the random spatial placement of nodes and non perfect power control. Unfortunately, the increase in time complexity for such simulation does not allow us to perform it.

6. Proposal of using a wireless multihop topology for an automation system

There exists a plethora of different wired industrial network standards (e.g., CAN, ControlNet, DeviceNet, EtherNet/IP, LonWorks, P-NET) and from the beginning industrial networks were not considered as networks but instead as serial buses [33]. The standards have emerged from different problems that the industry wanted to be solved within for example a factory floor. The trend within industrial automation systems during the last years has been to use commercial-off-the-shelf (COTS) components such as high-speed Ethernet. However, at the lowest level where for example sensors are connected does not require these high-speed solutions due to the fact that sensors do not generate such large amount of data. The industry is using more networks than ever to communicate data between different processes and the automation part of the network is often merged with the business part. This increase in networking requires more cables (yielding more expenses) and it is here where the wireless networking has its main advantage as a cable replacement. In an industrial network the nodes are connected through process affiliation rather than physically implying that the amount of wires could be even more and different network segments could be placed “above” each other.

The industrial network standard called P-NET (the name is derived from process networking) has a wired network architecture very similar to the proposed wireless clustered network architecture in this paper. The P-NET is a Danish fieldbus standard dated back to 1980s and it provides means of connecting process transmitters with PLCs [34].

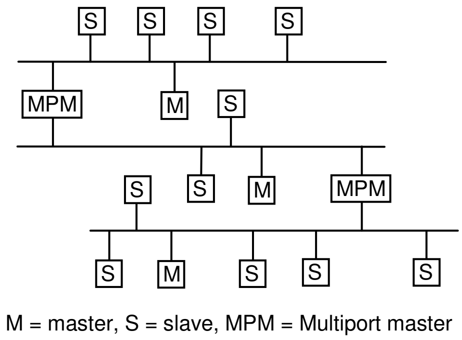

Figure 8. Example of a wired P-NET.

The embodiment of the P-NET is based on masters, slaves, and multi-port masters, where up to 32 masters can control 125 slaves referred to as a network segment. The network segment could be connected to other network segments by the use of multi-port masters. The P-NET is known as a multinet protocol because of the extension properties through multi-port units and this gives the ability to structure the network into hierarchical layers where the different layers are for example sensor level, device level and control system level. In Fig. 8, an example of P-NET is depicted. Since P-NET offers great extension possibilities it can often be used to run an entire factory floor.

Within a network segment masters poll their slaves and if there is more than one master on one network segment then the available resources must be shared between the masters since they cannot send at the same time. This sharing is performed by using token passing, meaning that the master must hold the token to have permission to send. This network architecture has similarities to the one we have suggested. Both use masters and slaves and the communication between different segments are done through multi-port masters in our case dual-radio gateways. The wireless multihop network also introduces redundancy without the need for extra resources compared to the wired case where more cables have to be used.

We are proposing our clustered wireless network based on dual-radio nodes utilizing FHSS to build wireless automation network topologies similar to the here described P-NET. Since industrial networks are semi static and the network topology is often known in advance, orthogonal hopping sequences could be used. The dual-radio gateway node enables the formation of both vertical interconnections as horizontal interconnection of clusters. This means that it is possible to build hierarchical architecture similar to the ones possible in P-NET, where the different levels could be the field level, cell level and control level and so forth in an industrial setting. In an FHSS system with orthogonal codes concurrent transmission between clusters can take place.

7. Conclusion

In this paper both a cluster collision avoidance mechanism and a proposal of using the wireless clustered multihop network in an automation network is presented. The neighbor cluster collision avoidance (NCCA) is used in a frequency hopping spread spectrum (FHSS) system having a clustered wireless multihop network topology. The main function of NCCA is to prevent adjacent clusters from utilizing the same frequency channel at the same time instant. The simulations conducted so far reveal that the NCCA with one hop cluster collision avoidance provides a capacity gain compared with the case without NCCA. The simulation of the optimally performing NCCA also reveals that more capacity gain is achievable if collisions in the time-frequency domain with clusters more than one hop away are taken into account. This system capacity gain is important, but the feature that makes the NCCA so beneficial is that it extends the stable region of operation. The goal is that the system capacity should settle on a constant value and not go towards zero when the system is overloaded.

The simulations also show the large impact that the path loss exponent, n, and the signal-to-interference (SIR) threshold have on the aggregated system capacity. Not much can be done to influence the path loss exponent; one can only conclude that high spatial isolation is achieved when the path loss exponent is high. The performance is highly dependent on the *SIR* threshold implying that the design of the wireless receiver is important. A wireless multihop network with spatial channel reuse is an interference limited system and not a noise limited system meaning that the *SIR* threshold is substantially more important than the signal-to-noise (SNR) threshold for the receiver design.

An ordinary Bluetooth device, which supports v. 2.0 of the Bluetooth specification [23], is able to join the cluster network topology suggested here as a slave node. However, it can never act as gateway or master inside a cluster and it is restricted to use single slot packets, i.e., DM1 and DH1 packets.

The NCCA mechanism is preferable when the network topology for some reason is not known in advance or a dynamic behavior is desirable. If the network topology is known and will be the same during the operation another approach for generating the hopping sequences is possible – the use of orthogonal sequences. An industrial network is an example of an often predictable topology and in this paper we propose to use our clustered wireless multihop network for an automation system applying orthogonal hopping sequences.

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