A Networking Perspective for Intelligent Utilization of Directional Antennas in Ad Hoc Wireless Networks: The TANDEM Approach

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Abstract

The ad hoc model has generated significant interest in the field of wireless (mobile and otherwise) networks in recent times. In the ad hoc model, the relationship between nodes that form a network are not fixed or predetermined, but rather the nodes communicate within themselves to "discover" the network configuration. Battery power conservation is of prime importance in such networks and is integral to problem areas such as routing, localization and management. Often the single largest energy expenditure is due to the wireless transceiver. In fixed wireless broadband networks, many times the wireless connections are point to point using a directional antenna. In ad hoc networks, most of the times a transmission by a node is targeted toward another specific node. In such a case, power is wasted by using a broadcast instead of a directional transmission. If the ad hoc network runs a localization algorithm and if a directional antenna is available, a focused beam may be used. Other transmissions may need to be broadcast because the location of the receiving node(s) may not be known. We propose a *tandem* scheme of using both broadcast and directional transmissions to optimize the use of battery power. In addition to studying the case for a specific network architecture of our own choice, we define a mathematical framework for quantifying the applicability of similar tandem schemes in various ad hoc architectures.

Keywords: Ad Hoc Networks, Beamforming, Localization, Wireless, Smart Antenna, MAC Layer, Tandem

1 Introduction

In the last few years, the *ad hoc* model of networking has generated increasing interest. In such a network, each node operates not only as a host, but also as a router, forwarding packets for other mobile nodes that may not be within direct wireless transmission range of each other. The network is dynamically self-organizing and self-configuring, with the mobile nodes in the network automatically establishing and maintaining routing among themselves as they move about, forming their own network "on the fly," without requirement for any existing infrastructure or administration. Such a network may operate in a standalone fashion, or may be connected to a larger infrastructure. This type of architecture has been called an *instant infrastructure* as well, because the routing infrastructure of the network is not predetermined, but is instead decided by the nodes as well. An ad hoc network is especially attractive for cases where the deployment of the nodes is not planned over a time scale of months (as in traditional networks) but over minutes, and it may be neither possible, nor desirable to plan the relative placement of nodes in detail.

The nodes may be mobile or, comparatively, static. Even a network in which all nodes are completely static may posses the essential characteristic of ad hoc network, in that each individual node does not know *a priori* how many other nodes share the network, or their relative positions, so that the routing infrastructure (*i.e.*, which nodes perform routing and on behalf of which other nodes) has to be decided cooperatively after deployment.

Possible uses of ad hoc networking include diverse scenarios, such as students using laptop computers to participate in an interactive lecture, business associates sharing information during a meeting, soldiers relaying information for situational awareness on the battlefield, emergency disaster relief personnel coordinating efforts after a hurricane or earthquake. In a wireless distributed sensor/actuator network, the node positions are fixed once deployed (by aerial drop, perhaps). Ad hoc sensor networks have the potential to sense and process the information from thousands of nodes and react to changes in the context and objectives. Weather monitoring, tactical awareness, tracking of animals, vehicles and personnel, warehouse and hospital inventory tracking are just a few examples of applications of distributed sensor networks. Another example of stationary ad hoc network is the fixed wireless broadband last mile Internet access.

The challenges facing the ad hoc paradigm are numerous. Since the same medium is shared by multiple nodes, the problem of medium access arises; however, unlike wireless networks with base stations, in ad hoc networks there is no centralized control and synchronization information. Various *MAC approaches*, with and without attention to QoS issues, have appeared in literature [1–5]. The presence of mobility implies that links make and break often and in an indeterministic fashion. Modifications of routing algorithms for wired networks works well when the degree of mobility is low [6–8], but for highly mobile nodes *routing* presents new problems in adhoc networks, including the integration of QoS considerations. Significant work has been presented in literature both for "on-demand" and "table-driven" approaches [9–15]. Location aware routing has been considered as a means of controlling flooding behavior in approaches depending on flooding [16–19]. Location awareness is important for adhoc networks in other contexts as well, and in some cases (e.g. sensor network) may be a primary function of the adhoc network: this problem is called *localization.* A global positioning system may be useful in some contexts but cannot be assumed in others; both approaches have been studied in the literature [20–25]. Other areas such as management, security, etc. also involve special challenges in the ad hoc context.

All problems in ad hoc networks share a common concern for *battery power.* While some ad hoc networks may enjoy a plentiful energy supply (e.g. fixed wireless broadband access), most wireless nodes rely on batteries and operate on a rather limited energy budget. In many cases (wireless sensor networks, Smart Dust [26]), because changing batteries after deployment is impractical, the useful life of a node is limited by the amount of energy available. A localization algorithm is useless if the nodes spend all their energy trying to locate themselves. A similar situation is encountered in routing. Therefore, energy conservation plays a prime role in wireless ad hoc networks.

In wireless nodes, the transceiver is often the major power drain. In fixed networks, a common solution to reduce transmitter power while maintaining link quality and SNR is to use directional antennas [27–35]. (There may be other benefits to using directional transmission which we articulate later.) In [27, 34], the benefits of using multiple directional antennas and receivers at the central base station of a wireless network are studied. The use of an adaptive array of multiple antennas at central repeaters is studied for the ability to receive single packets even if multiple packets are transmitted in the same time slot in an ALOHA like protocol in [30] and for the ability to receive multiple packets in the same time slot in [31]. Directional transmission is used in [29] to reduce interference and thus improve link quality. The study in [33] concentrates on designing a MAC protocol which can support the SEND primitive supporting the use of directional antenna. While these studies refer to traditional wireless networks rather than ad hoc networks, the use of multiple antennas for beamforming [36] can make directional transmission practical for mobile ad hoc nodes as well as for more traditional wireless nodes.

Another concern in using directional wireless communication in ad hoc networks is that the position of the nodes is typically not known *a priori* and therefore the directional transmission cannot be aimed at the neighbors. However, an entire range of new localization algorithms for ad hoc wireless networks were recently published [20–25]. Depending on the approach and the resources spent, localization precision varies significantly. However, at the worst, the nodes can locate themselves within a certain bounded region. Thus directional transmission becomes worthy of consideration in ad hoc networks.

However, it is very likely that every transmission in an ad hoc network cannot be made directional, nor may it be advantageous to do so. The transmission may be occuring before localization has proceeded sufficiently, or localization may have been unable to provide direction information for some pairs of nodes. Radio obstructions and reflection may make a destination node reachable using broadcast from another node, but not using directional transmission. It is likely that sometimes a broadcast (or multicast) is preferable to a unicast, especially if the source and the destination are close to each other or if the transmission has multiple destinations within the broadcast range.

Nevertheless, we feel that directional transmission should not be ruled out for ad hoc networks, even if it can be used only for some transmissions and not all. It is likely that saving battery power on even some of the transmissions can produce significant benefit on the whole. The two methods (broadcast and directional) can then be used in *tandem*, the choice depending on the context of the transmission. Motivated by energy conservation, we present a mathematical framework for analysis of the benefits and trade-offs of a tandem transmission approach.

These considerations are also comparatively independent of the mechanism of beam formation, as is the mathematical framework in Section 3. For example, it is possible that wireless optical communication technology could provide an alternate means of communication for ad-hoc nodes utilizing broadcast radio as their primary communication mode. Our model would be equally useful to such a case. This is why we have chosen to characterize this study as a tandem communication mode, the omnidirectional mode and unidirectional (possibly high bandwidth, low energy) mode used in an integrated strategy.

The rest of this paper is organized as follows. In Section 2 we present our proposal of utilizing both directed and broadcast communication in ad hoc networks. We describe the basic strategy, as well as point out benefits that can result with specific ad hoc network assumptions. We present a general mathematical framework in Section 3 for quantifying and evaluating the benefits for given assumptions about the ad hoc infrastructure as well as device characteristics. Section 4 describes an example of how this strategy could be practically used in a MAC layer protocol. Section 5 concludes the paper.

2 Tandem Transmission

The basic idea of the tandem scheme is easily stated: “Prefer a directional transmission over a broadcast one”. When localization has proceeded sufficiently that the direction of a destination node is known at a source node, we employ a directional transmission rather than a broadcast. Below we articulate the benefits that can be obtained from this approach.

2.1 Basic Benefits

It is reasonable to assume that the nodes go through an initial period of exchanging “hello” message after which each node i can partition the set of nodes $\mathcal{M}$ into a set $\mathcal{N}$ of “neighbor” nodes it can hear directly and the rest of the nodes $\mathcal{M}\backslash\mathcal{N}$ that it cannot. For the moment, assume that $\mathcal{N}$ is also the set of nodes which can hear node i directly. This information will obviously become obsolete; in a network of mobile nodes, the movement rate of nodes determines the timescale over which this information is valid, but even for static nodes, this information becomes outdated when nodes die, new nodes are introduced, or changes in the environment changes the reception characteristics of the network nodes (for example a radio obstruction could appear or one could be removed). However, there is in each case a timescale over which each node is reasonably certain of the set of neighbors $\mathcal{N}$ it can directly reach. While the relative location of the nodes in an ad hoc network is by definition not predetermined, the process of localization can provide (increasingly better) partial information once an ad hoc network is put into operation. At any time, an ad hoc node has a subset of $\mathcal{N}$ the direction component of whose location is known to it. There are two kinds of nodes in $\mathcal{N}$, ones with which i wants to communicate and ones with which it does not: typically all nodes of $\mathcal{N}$ fall in the first class. While a broadcast omnidirectional transmission is the only means available to i to communicate to nodes whose direction is not known to it, typically the localization information available to i will be best for those nodes near it and therefore more likely to be in $\mathcal{N}$. Thus it is likely that over the timescale that $\mathcal{N}$ remains valid, i can communicate to most nodes it communicates to directly using directional rather than broadcast transmission, and this will result in significant battery power savings.

On the other hand, node i can choose to channel the entire power available for a broadcast transmission into a directional one. In this case, the signal strength seen by a neighbor node j reached in this manner is significantly better than if i had used a broadcast transmission. Consequently, the SNR is higher and can support a higher data rate. Alternatively, if node i decides to use the broadcast power level, but is content with the data rate, then it can potentially now reach other nodes which it could not have reached directly using only a broadcast. Thus this allows node i to expand the set $\mathcal{N}$, reducing possible delay or loss probability at an intermediate node. In addition, the battery power of some node j which would have had to route the transmission from i before is saved. Thus three types of possible benefits arise in networking terms from the tandem strategy:

1. Reducing link cost (lower transmission power),
2. Increasing link bandwidth (more focused use of power), and
3. Greater connectivity (reaching nodes unreachable by broadcast).

Finally, these benefits may be combined to a certain extent. For example, it may be possible to reach a previously reachable node with a higher bandwidth *and* lower power than broadcast.

2.2 Networking Perspective

As noted above, the directional transmission can provide benefits in terms of network components. There are additional benefits from a networking perspective of the use of directional transmission.

Reduce Collisions: In a broadcast radio environment, a transmission by any station will cause a collision with any overlapping transmission by another station at every receiver that is in range of both transmitting stations. Collisions reduce the bandwidth utilization and increase packet delays. If, however, one or both transmitting stations were to use directional transmissions, the collision would be averted in many cases. This would improve the characteristics of both links, and improve network throughput as a whole.

Security: In a broadcast environment, every station within listening range of a transmitting station can receive the transmission, even if the data being transmitted is intended for only a single receiver. While this is not necessarily undesirable, in some circumstances this may give rise to security concerns. Such concerns can be addressed by authentication methods such as encryption, but many such approaches are vulnerable to statistical attacks. Directional transmission can reduce the fraction of communication (possibly encrypted) between two stations that can be observed by a malicious outsider, thus enhancing the security in the network.

Quality of Service: As we mentioned above, the tandem strategy can create greater connectivity in the network. Thus node pairs which can communicate only through an intermediate node utilizing broadcast may be directly connected with a directional transmission. This eliminates possible delay and loss at the intermediate node, and thus QoS guarantees are easier to make and keep. QoS routing is an active area of research in ad hoc networks [37–40], and it should be possible to integrate tandem strategies to obtain benefits in this area.

From a networking perspective, most of the above can be considered as a benefit from a data link control (DLC) layer with enhanced functionality and features. Since different links are discovered and updated by this functionality, it can be considered a sub-layer over DLC, integrating the link management of multiple links. This is the approach we take in Section 4.

2.3 Localization

It is obviously impossible to adopt a tandem approach without some effort toward localization. Thus the necessity of undertaking localization is part of the overhead incurred in a tandem approach. However, this need not be entirely a disadvantage. Localization is often a desirable goal in ad hoc networks because of other reasons and may be a primary goal of the ad hoc network. In addition, the localization effort may itself benefit from the tandem approach.

Of the different possible physical information that may be utilized by localization algorithms, one is the angle-of-arrival (AoA) [41]. In this approach, an ad hoc node measures the angle at which an incoming transmission is received, and this provides the direction component of the location. Nodes equipped with directional transmission equipment can enhance localization by utilizing the complementary approach as well, since such nodes can also decide the direction an outgoing transmission takes. This information can be embedded in the outgoing transmission and can either substitute, or enhance the AoA information measured by the receiving node. Moreover, the direction information is implicitly obtained for any node that responds to a directional transmission.

Another way in which the tandem approach can help localization is by fine grained characterization of the time when localization information is obsolete. If node i uses directional transmission to reach node j using the best localization information available for node j, and at some time node j stops responding to directional transmissions but is still reachable by broadcast, this can indicate that the localization information for j is obsolete (perhaps because the node has moved) and can trigger a localization attempt at i. It is not only possible to keep localization information more up-to-date, but localization efforts have to be made in small units. This means that the remaining localization information, which is still up-to-date, can be used in localizing the "lost" node.

2.4 Costs

Naturally, the tandem approach has costs associated with it which must be weighed against the benefits in designing an ad hoc network. These costs may be broadly categorized in two categories. The first category includes costs that are comparatively inflexible and must be incurred in any tandem approach, and is dominated by the cost of equipping the ad hoc nodes with directional transmission equipment. Obviously, no tandem approach is possible without incurring this cost. Of course, it is possible that different grades of directional equipment be used for different nodes, or that some nodes have such equipment while others do not. From a network wide point of view, there remains some cost to be incurred if any tandem benefit is to be obtained from that network as a whole. During network operation, the tandem approach requires each node to perform more processing, which incurs a cost either in terms of the extra processing power (including possibly more memory), or possible latency in the operation of each node, and these costs, too, must be borne. We call these the *base costs*.

The other kind of cost is more flexible, and whether such a cost is incurred depends on the specific tandem approach, and we call these the *tunable costs*. Consider an ad hoc network in which a table driven rather than source driven (demand-based) routing protocol [6, 7] is used. An ad hoc node i following the tandem approach would very likely maintain a database of current information regarding the modes (broadcast or directional) by which each neighbor node is reachable, together with associated transmission costs. This information can be seen as part of the routing information possessed by that node. The transmission cost incurred by node i at each transmission of the routing table is increased because of this tandem information, and must be counted as a cost of the using tandem approach. However, this cost is tunable because node i can choose to send less than the complete overhead in the routing table, instead sending only the most significant additional information. As an extreme case, node i can send only the same information as it would without following the tandem approach, using the tandem information only locally: in other words, tandem information is treated as encapsulated in a layer lower than the networking layer and is not considered to form part of the routing information.

There may be many other tunable costs. Potentially, a whole class of messages may be exchanged between nodes in some specific tandem approach for the specific purpose of supporting that tandem approach. Examples of such messages may be polling messages for the purpose of locating a lost node, or "keep-alive" messages which allow one node to track another's position. Alternatively, some or all of the normal messages exchanged in the ad hoc network could carry some tandem overhead in terms of extra information to facilitate the tandem approach. For example, we can create a protocol in which every message header contains the location (or location estimate) of the source node in global co-ordinates. In counting the cost of such overhead, we must be careful because the information could also be useful to some other function of the ad hoc network, such as localization, and the cost must be weighed against both benefits jointly.

3 Quantitative Framework

It is clear from the discussion in the previous section that there can be a large number of different approaches that all utilize the tandem concept, and the precise formulation of the cost and benefits will be very different for different strategies. Thus it is impossible to produce a mathematical expression or formulation which will be applicable to all possible uses of the tandem concept. Nevertheless, a basic description that should apply to any such tandem approach can be conceived. While too general to be of any use in itself, such a mathematical description would form the basis of any precise formulation of some specific tandem scenario and hence is of fundamental interest. In this section, we point out the quantities of interest in such a description and their interrelationships.

In what follows, we conceive of time being divided into segments that we refer to as *operational epochs*. Such an epoch is any duration of time which is stochastically representative of the lifetime of the ad hoc network as a whole. For example, an ad hoc network might go through two distinct phases, in the first of which the nodes only communicate to build up routing tables and localization information, and do not communicate user data; while user data is carried in the second phase, possibly with routing and localization updates as well. This network may alternate between these phases an extremely large number of times in the lifetime of the network. Each time the network cycles back from the second phase to the first phase, we consider one operational epoch to end and another to begin. A different network may have other different phases, such as route discovery, localization, etc. and the phases may overlap.

Different operational epochs may be of different length for the same network. For some protocols, the only possible choice of epoch may be to consider the entire lifetime to be a single epoch, while for others there may be billions of epochs in the lifetime, each lasting only a few seconds. The essential characteristic of the operational epoch is that the value of each key performance and operational variable is either exactly the same, or drawn from the same statistical distribution, in each epoch. For example, consider the ratio of routing messages to messages containing user data seen by a node. In a network which operates in two phases as above, the ratio is high in the beginning but low later on in an epoch. However, if the ratio is considered over each entire epoch, it is more likely to describe an essential characteristic of the routing protocol and other network characteristics.

All the following quantities are meant to be valid or measured over operational epochs unless we specifically mention otherwise. The relationships and any conclusions to be drawn from them are therefore also valid over each epoch, statistically, and hence over the lifetime of the network, though they may not be valid over durations smaller than an epoch.

Normal Cost: This is the cost of the network or node in terms of equipment and capabilities (other than battery cost) that would be needed *without* supporting any tandem operation, in some appropriate units. Unless the network lifetime consists of exactly one epoch, this cost much be apportioned in some appropriate way (e.g., amortized) over the lifetime and the appropriate value used for each epoch. We denote this cost by C_{n0}.

Basic Tandem Cost: This is the cost of the network or node as above, incremented by the *additional* baseline cost that must be incurred if the tandem strategy is to be supported. As mentioned above, this largely consists of the equipment cost of directional antennae, additional processor and memory costs. This cost must be similarly apportioned to epochs, and expressed in similar units as above. We denote this cost by C_{nt}.

Normal Total Transmission: The total number of bytes N_{b0} transmitted when the tandem strategy is not used.

Total Tandem Transmission: The total number of bytes N_{bt} transmitted when the tandem strategy is used.

Normal Battery Cost: The cost C_{b0} of the battery power required to transmit N_{b0} bytes when the tandem strategy is not used, expressed in the same units as above.

Tandem Battery Cost: The cost C_{bt} of the battery power required to transmit N_{bt} bytes when the tandem strategy is used, in similar units.

Signaling Overhead: The number of bytes transmitted exclusively as control information to support the tandem operation, expressed as a fraction of the total number of bytes transmitted, including both user data and control data unrelated to tandem operation. As we mentioned above, these bytes may be contained either in dedicated control messages or may form part of the header overhead of other messages. We denote this ratio by R_s.

Retransmission Overhead: When a directional transmission is not successful, most realistic tandem approaches would attempt to resend the message using broadcast transmission. Thus the directional transmission is wasted and the cost of that transmission must be counted as a cost incurred due to the tandem strategy. Note that this cost is incurred whether the broadcast transmission succeeds or not. We consider the ratio of bytes transmitted in such unsuccessful directional transmissions to the total number of bytes transmitted, and denote it by R_r. This term must be adjusted appropriately if the tandem strategy does not necessarily use a broadcast message when a directional one fails; we do not consider this scenario.

Directional Power Gain: The factor F_{pi} by which a directional transmission requires less power than the same message transmitted using broadcast, if the signal strength at the receiver is no less than that for the broadcast transmission, under power level i. Different power levels may be used to transmit to the same node, and we make the reasonable assumption that the power level cannot exceed the power required for the broadcast transmission.

Directional Bandwidth Gain: The factor F_{bi} by which the bit transmission rate is improved if a unidirectional transmission of power level i is used to transmit, if the power level is no higher than that for the broadcast transmission. Thus this factor can also be seen as one indicating the reduction of power required to transmit a given amount of data.

Directional Transmission: The fraction R_{di} of the total number of bytes that are transmitted in a directed transmission at power level i.

Transmission Reduction: The amount of data which does not need to be transmitted because a node i transmits to another node k directly using the same power and bandwidth for a unidirectional transmission rather than a broadcast transmission to an intermediate node j which needs to retransmit it to node k, expressed as the ratio R_e of bytes of such eliminated transmission to the total number of bytes transmitted.

We can assert the following interrelationships for some of the quantities above:

$$N_{bt} = N_{b0}(1 + R_s)(1 + R_r)(1 - R_e) \tag{1}$$

$$C_{bt} = C_{b0}\tfrac{N_{bt}}{N_{b0}} \left(1 - \sum_i R_{di} + \sum_i R_{di}(1 - F_{pi})(1 - F_{bi}) \right) \tag{2}$$

Equation 1 defines the relationship between the numbers of bytes that perform the same function (in terms of both user data and any control overhead unrelated to the tandem approach) with or without the tandem approach. Equation 2 defines the battery power needed to transmit the same: the first two terms inside the parantheses on the RHS accounts for the broadcast transmission under the tandem scheme and the last term account for the directional transmissions at the various power levels. We make the reasonable assumption that the battery power required per byte broadcast remains the same. Now we can express the total cost incurred by not using the tandem strategy and while using it, which we denote by C_0 and C_t respectively, as:

$$\begin{aligned} C_0 &= C_{n0} + C_{b0} && (3) \\ C_t &= C_{nt} + C_{bt} && (4) \end{aligned}$$

Thus we have the total costs which must be compared to evaluate the tandem strategy. It might appear that we need to normalize these costs by taking into consideration the number of bytes that are being transmitted, since this number is different with and without the tandem strategy. However, note that the transmission of N_{bt} bytes accomplishes the same amount of useful data transfer in the network using the tandem approach as the transmission of N_{b0} was before, thus the costs can be compared. Therefore, for any tandem strategy to be worth using, it must satisfy:

$$C_t < \alpha C_0 \qquad (5)$$

where α is a design factor less than or equal to 1. Further, for two otherwise comparable tandem strategies, the one with a lower value of C_t is more cost-effective, thus the tuning of tunable parameters in the general tandem strategy may be seen as an optimization problem.

Note that a few of the quantities refer to the case where no tandem strategy is being used, while others reflect the characteristics of specific tandem strategies. When evaluating any specific tandem strategy, we would consider the values of each quantity under that strategy, and apply the expressions above to consider its usefulness.

The quantities above can be interpreted either as relating to individual nodes or the network as a whole, and can thus be used in two ways. We could only consider the network as a whole and assume that the tandem strategy would be adopted identically by each node, thus this is a centralized approach. On the other hand, we might want to characterize the cost-effectiveness of the tandem strategy on a per-node basis, and evaluate the expressions above for each of them. It is possible that in that case different nodes might make independent decisions as to whether (or to what degree) they adopt the tandem approach. However, not only would this be more complex, it would also be necessary to interpret each quantity carefully with respect to such a decision. For example, the base tandem cost C_t must be treated differently from the tunable costs, since a node cannot dynamically decide to have the directional equipment installed or uninstalled. Others quantities may be difficult to determine on a per-node basis. For example, the factor R_e would be difficult to estimate at the best of times, but it appears to be quite challenging to characterize for a specific node.

It is likely that candidate tandem strategies would be sufficiently complex that none of the quantities above can be determined in a straightforward way, but more importantly, it will very likely be impossible to translate even a simple tandem strategy into values for the above quantities without making severe restrictions as to the position, number and nature of the ad hoc nodes, thereby violating the very essence of the ad hoc networking concept. Thus we should view the above quantities as forming a statistical estimate of the underlying concepts. Because we apply these considerations only to operational epochs, which are statistically similar to the lifetime of the network, the above considerations still have relevance.

4 A Tandem MAC-layer

In this Section we will present a simple tandem MAC (TMAC) layer capable of taking advantage of the tandem capabilities of a node while hiding the implementation details from the upper layers. This TMAC layer is only one of many different approaches which can exploit the the ideas presented in this paper.

Figure 1 depicts the main components of the proposed TMAC layer. The communication interface with the layers above and below is implemented through *send* and *receive* functions. Each software module is enclosed in a box. Data flow and interactions between the entities are depicted by arrows. The localization database (LDB) contains a list of all nodes in the network together with their locations (or location estimates). The neighbor database (NDB) contains a list of all neighbor nodes and other information used by the TMAC send routine to decide on the send method. A detailed description of each module is given below.

Logical Link Layer According to OSI reference model [42], the upper part of the data link layer is the logical link control. Depending on the particular networking stack used, functions like error correction and detection, acknowledgments of correctly received packets and link flow control may be implemented at this layer.

TMAC Layer This is the layer introduced in this Section. Its function is to hide the details of the tandem system from the upper layers. Different components will be detailed below.

MAC Layer This is the classical MAC layer. Its main function is to allow efficient access of multiple nodes to the shared medium. There might be different MAC layers for the two different methods (directional and broadcast), for example, a MAC layer such as the one proposed in [33] may be used for the directional send. The context of the actual means of directional transmission may also be pertinent; commonly used wireless MAC layers might make poor choices for a directional optical communication (e.g. laser).

Physical Layer In this layer we clearly have two different functions, one for each mode of transmission. While it is conceivable that we might also have two different functions for broadcast and directional receiving, we will assume for simplicity that only “broadcast receive” is available.

Localization The localization module is responsible for finding (approximate) positions for all nodes in the network. This might be as simple as reading the GPS coordinates from a GPS receiver and broadcasting them to the entire network. Recently, a number of alternative, GPS-less, approaches have been proposed in literature [20–25]. The precision of the localization algorithms depends on the hardware available and the method employed. While only one method takes directional transmission explicitly into account [24], most of them can be extended to use the directional capabilities of the nodes for an increased flexibility and precision in localization. The localization procedures are triggered either by internal localization mechanisms (specific to each approach), or by the neighbor discovery protocol. If the neighbor discovery protocol determines that a neighbor changed its position (either by being missed by a directional beam, or by getting out of range), the localization procedure may be notified to attempt to find the missing node.

LDB - Location Database Each node in the network will have one entry in this database (including *this* node). Each entry in this database will have two fields: *node id* and *location estimate*. The database is updated by the localization algorithm. The database can be read either by the upper layers through the function “Get location” (useful for example in location aware routing, or at the application layer), or by the

"Neighbor discovery" module, which can use the location information to estimate the direction and range of the neighbors.

Neighbor discovery This module can use any of the two send methods available to determine the set $\mathcal{N}$ of reachable neighbors. In both cases, a "hello" type of protocol can be used to determine reachability and, eventually, link quality. For broadcast, the protocol is in no way different from typical neighbor discovery. For the directional communication node, the neighbor discovery protocol will make educated guesses about the whereabouts of the neighbors based on the position estimates available in LDB.

It is possible to improve the precision of the localization as a result of the (directed) neighbor discovery. In this case, the localization procedure notified of such an improved estimate will update the LDB. Figure 2 shows the algorithm this module must execute.

NDB - Neighbor database Each neighbor may have one or more entries in the neighbor database. An entry has the following fields:

Node id: used to uniquely identify the nodes (e.g. MAC address).

Type of transmission: either broadcast or directional. If a node can be reached through both methods, at least two different lines will be present in the database, one for each method.

Direction: for the directional transmission, the direction δ of the transmission is needed, such that the beam can be "steered" to the appropriate direction. The direction can be easily computed by accessing the location database and finding the positions of *this* node and of the destination node.

Power: assuming that the transmitter supports it, it might be possible to reach a destination node using different power levels. For each different power level of successful transmissions a different entry will be generated in NDB.

Bandwidth: Typically, different power levels will result in different communication link characteristics (e.g. bandwidth, bit error rate (BER)). Here we assume the bandwidth information is of interest and is maintained in the database, in some suitable units such as Mbps.

Cost: Optionally, for each entry there might be an associated cost which can be used by the TMAC send function to compare alternative options, or by the upper layers (e.g. to compute shortest paths for routing).

An example of such a NDB for node 7, corresponding to the situation presented in Figure 4 is presented in Table 1. In this example, it is assumed that the transmitter can use four different power levels (1-4). For different power levels, corresponding broadcast ranges are depicted in Figure 4 as concentric rings. In this case we assumed that node 5 could not be localized, and therefore only broadcast transmission is available. (As an alternative strategy, the neighbor discovery protocol may search the entire space for it.)

Node	Type	δ	Power	BW	Cost
5	Broadcast	N/A	3	2	7
5	Broadcast	N/A	4	5.5	10
2	Broadcast	N/A	4	1	10
2	Directional	102°	2	1	2
2	Directional	102°	3	2	6
2	Directional	102°	4	5.5	8
11	Directional	317°	4	1	8

Table 1: NDB for node 7 in the configuration of Fig. 4

The information in NDB can be read either by the TMAC send module, which can take a decision based on the options offered by NDB, or it can be read from the networking layer to assist in the routing decisions.

TMAC send This module takes the decision on which of the two physical layer send method will be employed for a specific packet for a specific neighbor node. *TMAC send* reads all the different transmission options for the given node from NDB. When no bandwidth requirements are specified by the layers above, the method with the lowest cost should be used. Alternatively, if a minimum bandwidth is specified, then the least expensive method which still satisfies the bandwidth constraint should be used.

Other strategies are possible. For example, the TMAC send function can adaptively choose the transmission method as a function of the traffic load: under low traffic loads, low power, slow transmissions can be employed and as traffic increases, the power can be increased to allow for higher bandwidth.

If the *TMAC send* function is unsuccessful, it may notify the neighbor discovery module to search for the missing neighbor (which in turn, if unsuccessful, may trigger the localization module). Figure 3 shows the algorithm this module must execute.

{Physical, MAC, TMAC, LLC} receive Since in this section we assumed only omni-directional receivers, these modules are no way different from any other wireless network receive modules.

5 Future Work

We have articulated an integrated strategy of using both omnidirectional and unidirectional transmissions in wireless ad-hoc networks for (possibly manifold) reduction in transmission power. We have presented a general framework for quantitative evaluation of many possible tandem strategies, and provided an example of such a general scheme in which the tandem capability is encapsulated in a value-added MAC layer.

In specific terms, there are many ways to extend our current work, and we are pursuing some of these. They include: specifying additional general tandem schemes, studying their tuning characteristics, creating simulation (and eventually real) models to evaluate the various quantities of the quantitative framework, and creating more precise mathematical formulations for precisely defined tandem strategies. Variations are possible in the details we have assumed; for example, we have assumed that a transmission is either broadcast or directional, but the solid angle of the directional transmission may be controllable and hence a characteristic of each individual transmission.

However, we feel that fruitful research can be performed in diverse areas stemming from, or with reference to, the tandem approach. QoS and QoS routing are likely to benefit from integrated consideration with tandem strategies. There may be advantages to the ad hoc network in terms of network security. If directed transmissions have a much higher bandwidth than broadcast ones (for example, if wireless optical links implement the directed transmissions), we may consider quite different approaches to network architecture; for example, architectures using asymmetric links and hierarchical routing could be considered. We could take the view that the directional and broadcast transmissions implement two completely different networks with some exchange points, instead of taking an integrated view such as in this paper.

Thus, we believe that the concept of tandem transmission strategies is a general and powerful concept, and we look forward to a large variety of useful studies in this area in the future.

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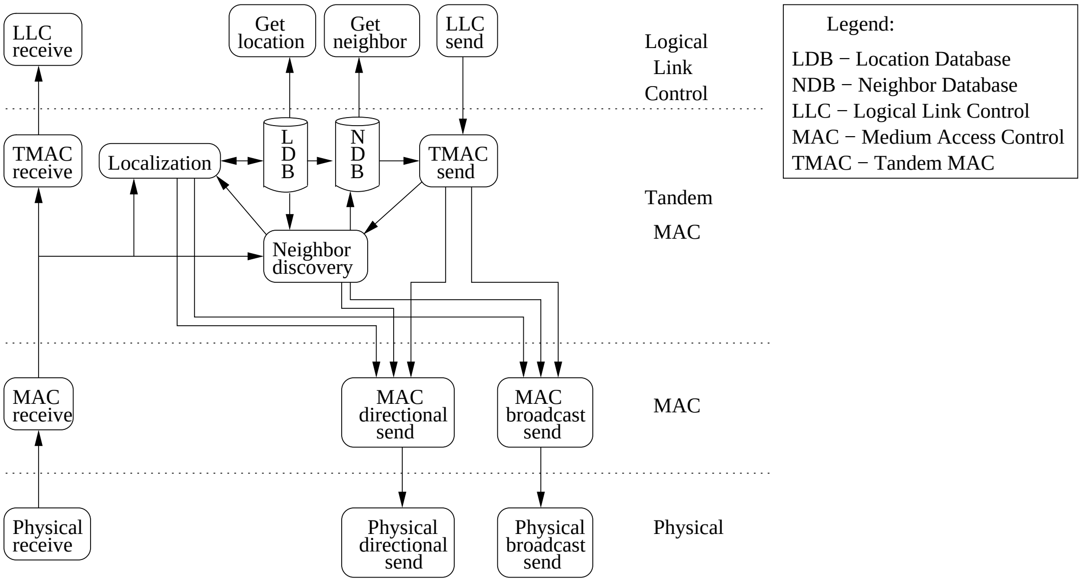

Figure 1: Sample tandem MAC layer

```
Procedure Neighbor_Discovery
  Returns: Success/Failure
  Parameters: [Destination Node ID (did)]

  /* When called with a parameter will look for a
   * specific node, when called without a parameter will look for all
   * the nodes which seem to be in transmission range. In the process
   * it will update the NDB.
   */

  If (did != NULL)
    return Directed_Neighbor_Discovery(did).
  else
    Broadcast Hello Message
    For each received message rmsg
      Directed_Neighbor_Discovery(rmsg->Source_ID).
    endfor
    For each node in the LDB which seems to be within transmission range
      Directed_Neighbor_Discovery(Node_ID)
    endfor
    return Success
  endif
endProcedure;

Procedure Directed_Neighbor_Discovery
  Returns: Success/Failure
  Parameters: Destination Node ID  (did)

  /*
   * It attempts to find a specific node specified by node id
   */

   Broadcast directed Hello message with different powers levels.
   Find node in LDB
   Send directional Hello message with different power levels
   If the position estimate in LDB is larger than the directional beam
   angle, scan the entire estimate.
   For each Hello answer (either directional or broadcast)
      write one entry in NDB
      notify the Localization procedure of successful exchange of
        hello messages and the parameters of the exchange.
   endfor;
   If there is at least one successful exchange of Hello messages
    return Success
   else
    return Failure
   end;
endProcedure;
```

Figure 2: Neighbor discovery algorithm

```
Procedure TMAC_Send
  Returns: Transmission result  (Success/ Failure [cause])
  Parameters: Destination Node ID (did)
              Message to be sent  (msg)
              [Minimum bandwidth  (minbw)]

  /* The procedure is in charge to choose the cheapest transmission method
   * which will still satisfy the optional bandwidth criteria.
   */

  Repeat
     Read all the entries from NDB which have Node_ID=did.
     Eliminate all the entries which do not satisfy the
       minimum bandwidth if specified.
     if at least one option is available
       choose the transmission method, power and direction with
       the smallest cost
       if (cheapest transmission is directional)
         outcome=MAC_directional_send(did, msg, direction, power);
       else
         outcome=MAC_broadcast_send(did, msg, power);
       endif;
     else
       outcome=Failure;
     endif;

     if outcome==Failure
        if (Neighbor_Discovery(did)==Failure)
          return Failure
        endif
     endif
   until outcome==Successful
   return Successful

endProcedure
```

Figure 3: TMAC send algorithm

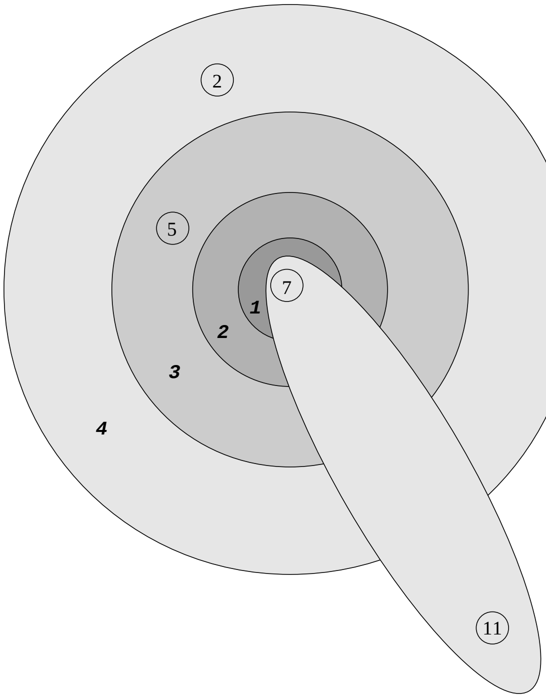

Figure 4: A sample configuration