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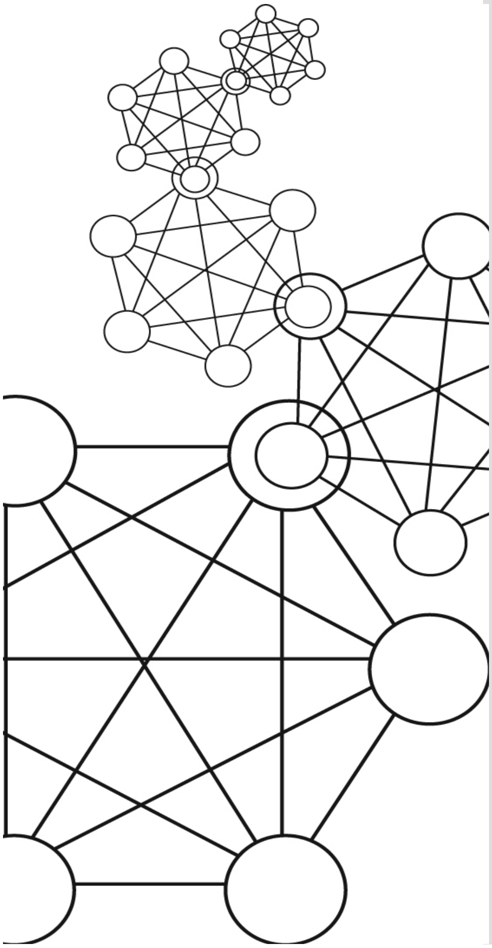
XTC+: a description and analysis of a topology control mechanism for MANETs



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Abstract

The Objective of topology control mechanisms (TCM) is to modify the natural network topology toward a determined objective. In MANETs the objective is to minimize power consumption and/or interference. In general topology control is achieved through deliberate changes in transmission power (and possibly other parameters such as antenna direction and channel selection) that directly affect the local connectivity of a node, and consequently affect the whole topology of the network.

By focusing on the stage in which information is collected in an existing topology control algorithm called XTC, this paper shows the possibility of extending the network performance optimization present in this algorithm. It is then an addition to an already existing optimization concept.

Key words

MANET
Topology control
Mobility model
Energy optimization
Interference
XTC algorithm
Information collection phase

XTC+: descripción y análisis de un mecanismo de control de topología para los MANET

Resumen

El objetivo de los mecanismos de control de topología (TCM) es modificar la topología de la red natural hacia un objetivo determinado. En los MANET el objetivo es minimizar el consumo de energía y/o de interferencia. En la topología general el control se alcanza mediante cambios deliberados en la potencia de transmisión (y posiblemente en otros parámetros como la dirección de la antena y la selección de canal) que afectan directamente la conectividad local de un nodo y en consecuencia, afectan toda la topología de la red. Este artículo muestra la posibilidad de prolongar la optimización del desempeño de la red presente en este algoritmo, mediante el enfoque en la etapa en que la información es recopilada en un algoritmo de control de topología existente llamado XTC. Es entonces, un complemento a un concepto de optimización ya existente.

Palabras Claves

MANET
Control de Topología
Modelo de Mobilidad
Optimización de Energía
Interferencia
Algoritmo XTC

Introduction

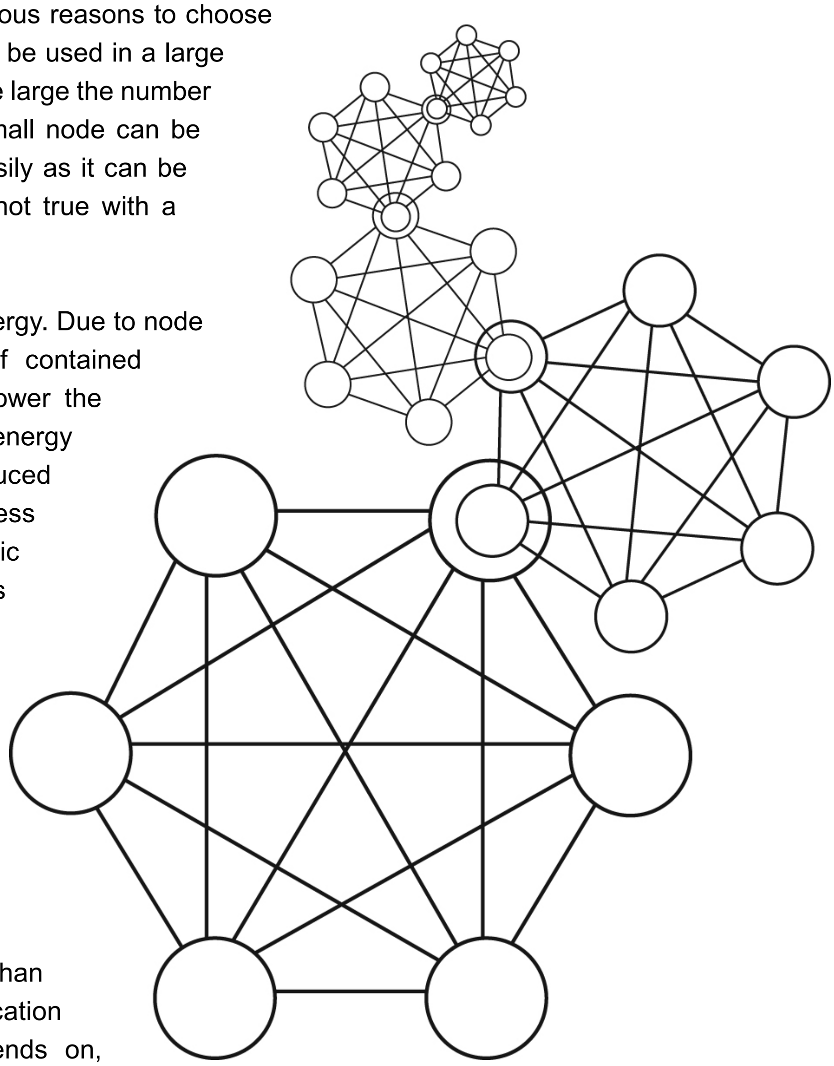
1. MANET

MANETs or Mobile Ad-hoc NETworks are auto configurable networks that are made up of mobile wireless nodes. The characteristics that differentiate them from other types of wireless networks are relative node mobility, reduced node size, lack of resources, communication interference and the fact that the nodes have to perform as host and routers simultaneously.

1.1 Qualities

Mobility is a critical factor and is present only when there is relative movement between the nodes. If the network were to communicate cars in a fast highway, there wouldn't be much relative movement. On the other hand, in an emergency situation, where the network serves as a communication infrastructure for rescue teams in a disaster area, the movement would be relative and chaotic. In general, in a relatively static network the effort of maintaining a structure that allows communication is much less than that of maintaining a dynamic one.

Size is relevant when node functionality is considered. MANETs can be used in the communication between large transport equipment in a shipyard as well as in communication between firefighters in the face of an emergency. There are various reasons to choose a small compact node because it can be used in a large variety of situations, where as if it were large the number of situations would be reduced. A small node can be placed in a person's backpack as easily as it can be placed on a bulldozer, the same is not true with a large node.



Lack of resources mainly refers to energy. Due to node mobility and size restrictions a self contained energy source is usually used to power the node. In the majority of cases the energy source is a small coin battery or a reduced solar panel. Moreover, when two wireless nodes communicate using an isotropic antenna, transmission energy grows quadratically with distance. It basically means that the farther a node sends a message the more energy it will be using. It then becomes more energy efficient to replace long distance links with several short distance ones. This is the general objective of most Topology Control algorithms.

Interference occurs when more than two nodes use the same communication medium at the same time. It depends on, among other things, network density, signal range, traffic, physical characteristics of the signal. Interference reduces communication efficiency and also increases energy use as the node has to retransmit every interfered message.

Ad-hoc nodes don't have a predefined behavior as in common networks. A node can be a host that produces and receives information to/from the other nodes. Additionally, it can also be a router that forwards information to the destination node. Moreover, the node has to be capable of performing the two functions, host and router, simultaneously.

1.2 Possibilities

The defined characteristics of MANETs offers an interesting spectrum of possibilities. Habitat monitoring applications where nodes are placed throughout a specific area to sense any given number of variables like those described in (Xu, 2004) can be considered applications for MANETs. If it were necessary, MANETs could participate in handling much more complex monitoring activities than those expressed in (Xu, 2004). More specifically, MANETs could monitor animal behavior by placing a mobile node on each individual.

A common scenarios for the use of MANETs are emergency situations. The auto-organizing network can serve as a temporary system replacing damaged communication lines or as a dispatch system for rescue crews like the one mentioned in (Crowcroft. *et al.,* 2005). Additionally it may allow the surveillance of hazardous geographic regions. Another interesting possibility is to use MANETs in war scenarios. The networks can be deployed to gather information of a region that has not yet been traversed by advancing troops. It can also serve as a surveillance tool in important tactical areas. As in emergencies it can also serve as a main or backup communication frame-work.

1.3 Challenges

The unique qualities and the listed possibilities set forth some very demanding challenges which will have to be overcome in MANET development. The correct administration of elements like energy is crucial to the longevity of the network, as seen in (Margi & Obraczka, 2004) and (Agrawal. *et al.,* 2001). Moreover, signal interference and security are recurring factors in all wireless networks and are elements that have to be addressed to ensure optimal network performance and correct information dissemination as shown in (Dhoutaut, Chaudet & Lassous, 2005), (Resta. *et al.,* 2005), (Zhan Song. *et al.,* 2004). Following the same line of ideas, nodes should have high tolerance to cope with extreme physical demands, like extreme temperatures (in a furnace for example), extreme and sustained pressure conditions (deep under water) and rapid pressure changes (when falling to the ground from a mobile platform like a car). Another important aspect to consider is the routing of messages through the mobile network which is necessary for communication between distant nodes (Akkaya & Younis, 2005), (Al-Karaki & Kamal, 2004), (Villasenor-Gonzalez, Ge & Lamont, 2005). But from all the aforementioned challenges, three stand out as the most crucial for the network operation: MAC (medium access control), resource administration and routing. This paper will focus on resource administration and more specifically, on energy saving strategies.

Challenges are also encountered within the investigation of MANET behavior. As (Resta, *et al.,* 2005) states, much work is being done with unrealistic models that only consider a subgroup of MANET situations. Moreover, the simulation of movement is a crucial matter when it comes to the analysis of any data (Xiaoyan, Gerla & Chiang, 1999), (Boleng, Davies & Camp, 2002), (Noubir, Lin & Rajaraman, 2002), (Mathur, Murray & Pesch, 2003), (Chaouchi, 2004), (Bettstetter, 2001). Interference models and their relation to topology control is not a trivial matter, and deductions that are made in this respect are not always valid (Wattenhofer. et. Al, 2004), (Johansson & Motyckova, 2005).

2. Related Work

To give a little sense of orientation, a mathematical structure that is often used to describe MANETs will be described, followed by a description of desired network behavior and, finally a list of different solutions that have emerged in the field. All of these will be related to the energy saving characteristics of MANETs.

2.1 General

The mathematical structure that is often used to describe wireless networks is a graph. The following is an attempt at a very brief explanation of the mentioned concept:

Let the graph *G = {V,E}* describe a network where V is a list of all the nodes contained in the network: *V = {a,b,c,d,e...k}* and E is a list of pairs that represent a link between two nodes. The pair elements must be contained in *V: E = {(a,b),(a,c)...}.* This structure can be extended to express aquality value for each element in *E.* So there could be an additional element in the graph description denominated *F* that contains the relation between *E* and some value representing the quality, *F = {[(a,b),0.45],[(a,c),0.9]….}.* The quality value would have a range of 0.0 to 1.0 and would be calculated using variables like distance, obstacle interference and environment noise.

2.2 Ideal Topology Characteristics

For MANETs to become a reality they must meet some requirements:

1. The network must be persistent in such a way that it functions for as long as the resources allow. This quality mainly refers to energy use and the way energy is managed so as to give the network a greater continuance.

2. The network has to do everything in its range of possibilities to stay connected. It is the norm in MANETs that the links stretch and change with the movement of the nodes. These types of situations must be addressed in real time so as not to end up with a disconnected network. Moreover, there will be situations where there is a break that has to be addressed through some type of mechanism that could be thought of as a Best Effort mechanism.

3. The network must be resilient to environmental havoc. If MANETs are to be used in emergency or war-like situations, they are most likely going to be constantly under great stress. The physical node design, along with the network, must be capable of taking a beating while still maintaining communication.

For the time being, we will concentrate on the first of the three points above and try to devise a mechanism that gives continuity while saving energy.

2.3 Topology Control Algorithms

In general, topology control algorithms receive a *G = {V,E}* graph and transform it into *G' = {V',E'},* where *V' = V* and $E' \subseteq E$ where the links in *E'* are optimized to fulfill a general objective. Additionally, all the pairs in *E* have weights that represent link quality. In other words, these types of algorithms modify the topology to get a certain behavior as a result. The following is a list of some of the most recognized topology control algorithms in the literature today.

Relative Neighborhood Graph (RNG): A link between node u and node v is selected if no node *w* exists such that *w* is closer to *u* than *v,* and *w* is closer to *v* than *u.* In other words if *MAX(d{u,w}, d{w,v}) < d{u,v}* then the link is not selected, where *d{u,v}* is the distance between node *u* and *v* (Yang, *et al.,* 2004), (Rajaraman, 2002) and (Supowit, 1983).

Gabriel Graph (GG): A link between node *u* and node *v* is selected if no node *w* exists contained inside the circumference formed by the diameter between *u* and *v.* Formally speaking, the link between node *u* and *v* will be selected if no node *w* exists such that $d^2\{u,w\} + d^2\{v,w\} \leq d^2\{v,u\}$ (Yang, *et al.,* 2004) and (Rajaraman, 2002).

Yao Graphs and θ-graphs: These are two approaches that are very similar. The basic idea is to separate the area surrounding each node into equally-sized triangular sectors. The node range would then resemble a sliced piece of pizza. The selection of the closest neighbor inside each sector is done after these are created. In Yao's case the sectors would be equally separated rays, and in *θ*-graphs case they would be sections of a fixed angle. The key to an optimum G' topology is to bound the number of sections or rays with a constant. Coincidentally, in both approaches, the constant is $k=6$, so the Yao approach would have a maximum of 6 rays, and the θ-graphs approach would have a maximum of 6 areas, with an angle of $\pi/3$ (Yang, *et al.,* 2004) and (Rajaraman, 2002).

XTC: This is an approach that does not need position information (like the previous algorithms). In general, a node *u* will choose *v* as its neighbor if no node *w* exists that is “better” than *v* and can be reached easier from node *v* than from *u* (Wattenhofer, *et al.,* 2004).

3. XTC

In the previous section, a very simple description of the algorithm is given. This section will give a more in depth look at the workings of the algorithm.

3.1 How it works

XTC is an algorithm that creates a network that is symmetric, sparse and connected (Wattenhofer, *et al.,* 2004). It is executed locally and is calculated using a link quality metric. This metric can be as simple as the distance between two nodes, or can be a value that not only represents node distance, but also includes models based on noise interference and traffic.

The XTC algorithm as described in (Wattenhofer, *et al.,* 2004) consists of three stages:

1. Neighbor Ordering
2. Neighbor Ordering Exchange
3. Edge Selection

The first stage is the creation of a neighbor order (list of neighbors $\aleph_u$) for local node *u*. Each element of the order contains a neighbor identifier and a related link quality. The elements with better link quality will appear before those with reduced link quality. The $\aleph$ character not only describes the neighbor order, but when used with neighbor identifiers can depict the position in which the nodes appear in $\aleph_u$. In this way, if node *w* comes before node *v* in node u's neighbor order, it would be expressed as $w \aleph_u v$. In stage one, node *u* transmits only once. It will send an advertising packet with maximum power while, at the same time, listening for incoming transmissions. When a transmission is received from a neighbor node *v,* a neighbor identifier is inserted into $\aleph_u$ using *v's* calculated link quality. At the end of the first stage *u* will have a neighbor order organized by link quality.

The second stage consists of sharing $\aleph_u$ with *u's* neighbors. At maximum power, node *u* will transmit a message containing $\aleph_u$ while, at the same time, collecting all the orders from its neighbors. The first two stages basically gather data needed for the execution of the algorithm in the third stage.

Figure 1. XTC Algorithm

1. Establish order $\aleph_u$
2. Share $\aleph_u$
3. $N_u = \{\}$ $\tilde{N}_u = \{\}$
4. while ($\aleph_u$ contains neighbors)
5. $v \leftarrow$ next neighbor in $\aleph_u$
6. if ($\exists w \mid w \in (N_u \cup \tilde{N}_u) \wedge w \aleph_v u$)
7. $\tilde{N}_u = \tilde{N}_u \cup v$
8. else
9. $N_u = N_u \cup v$

The third stage uses the gathered information to calculate a final topology. Figure 1 shows the pseudocode of the whole XTC process. This process is also explained in the paragraph following the figure. The first line is where node u creates its neighbor order. In line 2, it transmits $\aleph_u$ and receives its neighbor's orders. Line 3 initializes two lists: the neighborhood list that will contain *u's* Topology *(N_u),* and the rejected neighbor list *($\tilde{N}_u$)* that contains the neighbors that are reachable but are rejected. Line 4 expresses the fact that the algorithm traverses $\aleph_u$. In line 5 an element of $\aleph_u$ is assigned to *v.* Line 6 - 9 is where node *v* gets either chosen or rejected. Informally speaking, node *u* will form a direct communication link with node *v* if there is no node *w* that can be reached more easily from *v* than from *u* itself (Wattenhofer. *et al.,* 2004).

3.2 O-XTC in Dynamic environments

In situations where there is node movement, the previously described algorithm can only go so far. Moments after ending the while statement in step 4, the local node's neighbors and the local node itself will have moved out of their original positions, thereby rendering the calculated topology useless. In this case, the soundest thing to do is to repeat the process described in 3.1 indefinitely until the network is terminated.

Figure 2. O-XTC behavior

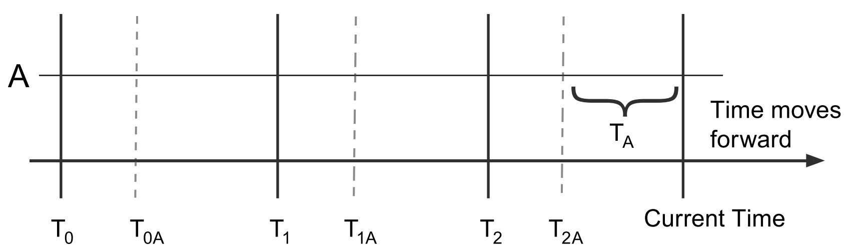


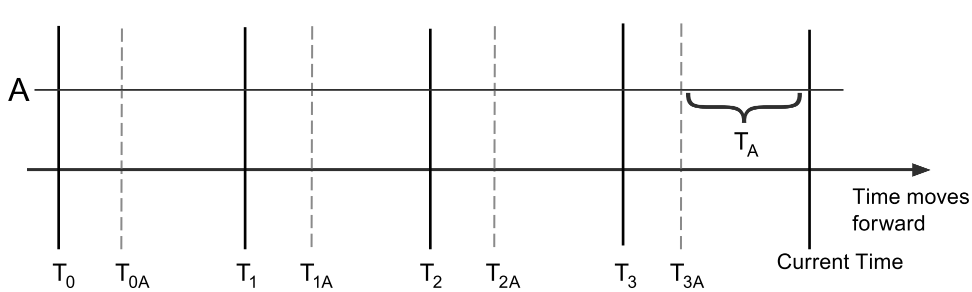
Figure 2 shows that the repetition is carried out by putting an XTC interval one after another. Be aware that the intervals expressed in the figure are made up by the three XTC stages (neighbor ordering, neighbor ordering exchange, edge selection). This approach will be denominated O-XTC.

3.3 Proposed approach XTC+

Intuitively, the O-XTC approach uses a great number of messages. It seems that excessive traffic can be reduced by modifying the way the information is collected. It is with this objective that O-XTC is redefined into XTC+. The main change is the reduction in the number of total stages. While in O-XTC there are three stages, XTC+ has 2. By taking away the "neighbor ordering" and merging it into the "neighbor ordering exchange" stage, XTC+ uses fewer messages while at the same time exhibiting a behavior that is comparable to O-XTC.

The idea behind XTC+ is to use the "neighbor ordering exchange" stage as an opportunity to gather the neighbor order itself. In other words the information shared in the stage that begins in T_1 and ends in T_2 is collected in the previous stage (Figure 3).

Figure 3. XTC+ behavior



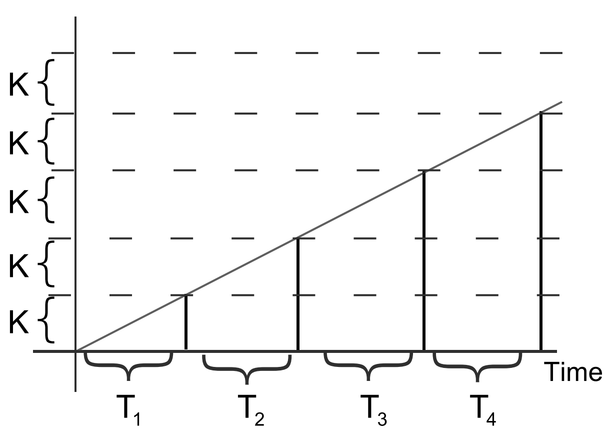
4. Analytical Description

It is very precarious to suggest that one model has better qualities than the other based only on the number of stages, especially when no analysis is done regarding the effectiveness of each approach. The objective of the following model is to give some insight into the possible behavior of the two topology control approaches, and also to have some sort of way to analytically compare them.

4.1 Change Model

Assume, for the sake of explanation, that the movement in a network can be described with a bi-dimensional function, like the one shown in Figure 4. The *x* axis is time and the *y* axis is the amount of change (which could be measured in the total amount of physical distance that each node traveled). The diagonal shown in Figure 4 would represent the amount of movement of the network as time passes. In this particular case the amount of change per time period is constant.

Figure 4. Change Model



Given the restriction imposed by the models themselves, the amount of change needs to be constant for this model. Although it is possible to have a system where the movement is not constant (it might be the norm for MANETs to have non constant movement among their nodes), the models described in this paper are not equipped to handle the variable mobility (understand variable mobility as a situation in which the total amount of movement in T_1 is different from other time intervals). An additional layer to the model must be created that addresses the various consequences that variable mobility bring into the system. This will left for future work and will not be addressed at this moment.

Further assume that for each period of time expressed in Figure 4 the total amount of movement can be neglected as far as topology control is concerned. In other words, the movement that takes place in these intervals is not enough to render the calculated topology invalid. As everything done inside the time interval has certain validity due to the "lack" of movement, the time interval will be denominated "interval of validity", or *IV.* After having assured that the movement in the *IV* is hypothetically irrelevant, it is necessary to assure that each model collects, calculates and uses the XTC topology. Each model behaves differently in order to comply with this characteristic. The following section will explain what each model must accomplish in order to complete the three stages successfully within the time interval.

4.2 Models in Change Model

The question is: how do O-XTC and XTC+ have to behave in order to collect, calculate and use XTC topology while, at the same time, having a valid topology representation for every moment in time? And how are these models compared once the first question is answered? Lets examine these questions in the next subsection.

Let the reader be reminded that a model interval is separated into phases. The O-XTC has 3 phases and the XTC+ has 2. Also important to keep in mind is that the interval of validity does not necessarily have to coincide with the interval of the model. Consider as well that XTC refers to the execution of the algorithm itself (step 2 through 9, Figure 1).

4.3 O-XTC

An important aspect of the O-XTC model is that it ensures that at the end of the interval, the topology is calculated from data that is contained inside said interval. This means that whatever is calculated at the end of the interval expresses the state encountered at the beginning of the interval. This is possible if complete synchronicity between all network nodes is assumed. Synchronicity is needed because inside each phase, all the nodes need to transmit a specific message. In the first phase, all nodes need to transmit (and receive) the “neighbor ordering” message. In the same way, in the second phase, the “neighbor ordering exchange” messages are interchanged. If all the nodes were not synchronized, it would be possible for some nodes to be in phase two and for others to be in phase one, therefore rendering the collected information in each node inconsistent. This synchronicity is only assumed and is not calculated into the change model analysis.

In the first run the O-XTC has successfully collected and calculated a topology. The next step is to give the node the opportunity to use the topology. This happens for the full extent of the next interval, in parallel with the calculation of the next topology. In other words the current topology is used until the next one is ready (at the end of the interval).

Keeping the aforementioned information in mind it can be stated that two O-XTC intervals are needed inside an IV for an accurate topology to be rendered at any point in time. This conclusion is obvious in light of the fact that inside an IV there is no perceivable change (subsection 4.1), and that two O-XTC intervals are needed to calculate, use and collect information for a topology control structure.

4.4 XTC+

In the XTC+ model, a situation occurs with the data received from the neighbors. In the worst case scenario a message can be received at the beginning of the interval. This message will contain a neighbor order that is calculated using information from one interval in the past. In other words, the topology calculated at the end of the interval contains data that dates back two intervals into the past. So XTC+ uses data from two intervals to calculate the topology.

As in the O-XTC model, the XTC+ will use the calculated topology until the next one is available. This means that another interval is needed besides the two that have already been used for the information collection and calculation of XTC.
keeping the aforementioned information in mind it can be stated that three XTC+ intervals are needed inside an IV for an accurate topology to be rendered at any point in time. Compared to the two intervals of the previous model, it seems that O-XTC has the upper hand. On the other hand, O-XTC assumes synchronization which, in itself, needs additional effort.

4.5 Comparison

For the comparison of the two models, the same network behavior must be assumed. This would mean that the IV for each model is the same, and therefore each model will render the same topology. So there is no sense in comparing the validity of each topology when they are the same. The number of transmitted messages (that directly translates into energy usage), on the other hand, can and is compared in the analysis. As the number of transmitted messages grows, the used energy grows proportionately. This means that the model that transmits less is the more effective one in terms of energy usage.

Let n be the size of the structure that represents the node ID. Let q be the size of the structure that represents the quality of the link. Let k be the number of neighbors. Let $M_{o\text{-}xtc}$ be the total amount of messages that O-XTC needs for one interval, and M_{xtc+} the total amount of messages for XTC+.

(1) $n + k(n + q) = M_{o\text{-}xtc}$

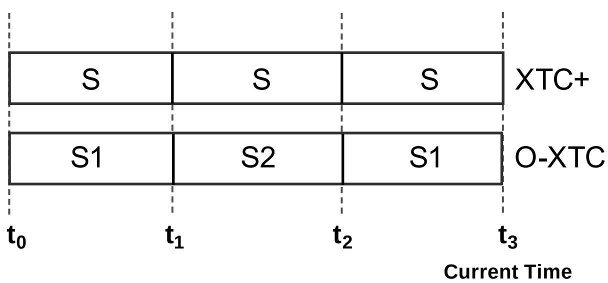
(2) $k(n + q) = M_{xtc+}$

(3) $2M_{o\text{-}xtc} < 3M_{xtc+}$
$2n + 2k(n + q) < 3k(n + q)$
$2n < k(n + q)$

Equation 3 shows how O-XTC uses fewer messages than XTC+. Moreover, XTC+ is dependent on the number of neighbors, and the difference between the models will increase considerably with the addition of new neighbors. As stated before, this is true for cases where the IVs are equal in each model.

There is, however, another method of analysis that we can use to visualize the behavior of the model. Considering the overhead for the two types of messages that are handled in the two models (“neighbor ordering” and “neighbor ordering exchange”) and also taking into account that the payload is most likely going to be compressed in some way, the two types of messages are of similar length.

Figure 5. Phase comparison



Additionally, every message sent has to have a minimal time in which to reach the transmission range. This is true for messages in all the phases of the model intervals. When you add up all the times of all the messages needed in one phase, you end up with a theoretical floor that, when broken, renders the communication inconsistent. Keeping in mind that O-XTC has 4 phases in an *IV* and XTC+ has only 3, the floor for each model is different. Additionally, if the messages are similar in length, the two floors can be compared.

With this in mind, there can be a situation where an IV has been reached that is shorter than the O-XTC floor. In other words, there is so much variability in the environment that the *IV* would have to be made shorter in order to cope with it. But in O-XTC's case, the IV cannot be made shorter because the time that messages need to propagate cannot be made shorter. XTC+, on the other hand, has only three phases (compared to the four of O-XTC) and can manage to shrink a little more.

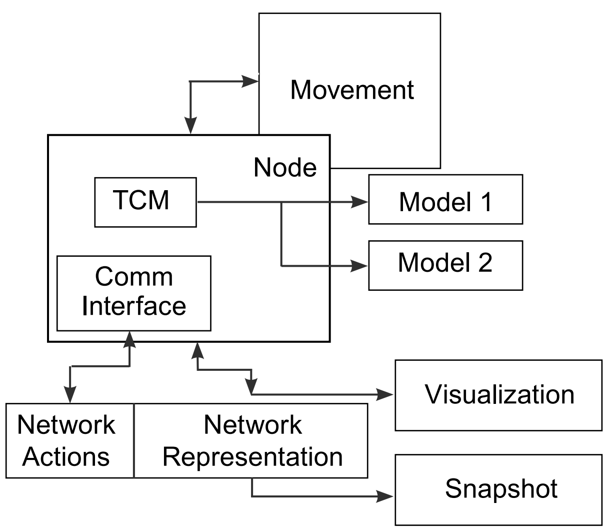
This situation is visualized in Figure 5 where the IV has been made as short as XTC+ can handle. It can be seen that only three phases of O-XTC can fit inside this IV. Since O-XTC has not yet reached the point in which it calculates the topology, there will be one phase in which the topology calculated in t_2 is useless. This would make the validity of the topologies calculated in the two models differ in some way. Assume that the amount of “neglectable change” that occurred inside the IV is c. In this case the topology calculated in t_2 by O-XTC will not take into account the c/3 change that occurs in the phase after t_3. XTC+, on the other hand, performs normally. This means that XTC+ will have more accuracy than O-XTC by a value of c/3.

Although XTC+ transmits more messages, it is ideal for situations in which the variability is extreme. This is mainly due to the reduced number of phases that XTC+ uses. Also remember that it was assumed that O-XTC was synchronous, but no real addition to the message count was considered in the equation. So in reality this comparison might render different results when the network synchronization is considered.

5. Simulation

The simulator's modules are described in Figure 6. The node module is the one that contains most of the functionality for the nodes. It has submodules that serve different purposes inside the simulation. The TCM submodule is located inside the node and is the generic interface for all TCM models. It is this submodule that contains the calculated representation. To access the representation, the node must make a petition to this submodule. The TCM submodule can be connected to any TCM that implements the interface definition. The communication interface submodule is also located inside the node and it serves as an interface to the network module outside the node. Any outgoing or incoming message must go through the communication interface. The node has variables that describe its position, these are located inside the node. The module that is in charge of changing these node variables is called the "movement module" and is located outside the node. This module describes the movement for all the nodes in the simulation. It also describes the periodicity with which the node's positions are changed. A Random Walk Mobility Model and a simple Group Mobility Model were implemented for the simulations. Only the Random Walk Model was used.

Figure 6. Simulation model



The network module is the one that has the description of the entire the network. It manages an array of nodes that represent the network. Moreover, the message delivering system is implemented in this module. The node's communication interface submodule communicates directly with the network module to transmit any message. When a message is transmitted, the network module calculates the range of the transmission based on the energy of transmission that the node specifies. The network module then delivers the message to the nodes that are inside the range of the sent message.

The visualization module is implemented for graphic visualization purposes. Its function is to periodically probe the network for the positions of the nodes and their represented network. The visualization module gives a complete view of the simulated area, the movement of the nodes and the connections that the nodes have amongst themselves.

The snapshot module is used to take snapshots of the network and keep them in memory for posterior use. Its interest is in the node position variables and the node representation of the network. It is with these snapshots that, at the end of each simulation, the accuracy of a model is calculated.
Finally, the TCM modules (Model1, Model2) are the ones that house each TCM. Each mechanism is implemented to be completely self-contained. In other words, all the variables and the related processes are contained inside the individual module.

5.1 Measured Variables

The simulations measured certain variables that describe how optimum one model is compared to the other. The objective of the experiment is to evaluate the behavior of O-XTC and XTC+ in MANETs. The experiment will use consumed energy and network representation accuracy to compare the behavior of the two algorithms.

Energy consumption is the first variable, and it will be measured by following all the outgoing control messages in a selected node. Only the part of the message that is strictly related to topology control information will be considered. The calculation is done by multiplying the bits in a message *(BPM)* with the energy required to transmit a bit *(EPB).* In this way, the total message energy *(TME)* is recorded each time a message is sent (Equation 4). When the simulation ends, the total energy spent *(TES)* by the node in topology control messages can be measured by adding all the *TME's* recorded as expressed in Equation 5.

(4) $TME = BPM \times EPB$

(5) $TES = \sum TME_n$

Let NR_{0u} be the neighborhood for node u at time t_0 calculated using one of the models, and let AN0u be the real neighborhood for u at time t_0. Let $diff_u(NR_{0u}, NA_{0u})$ be the difference between the two lists in *u.* The function counts the number of elements that are in one list but not in the other. The used diff() function is described in Equation 22.

(6) $diff(a,b) = [COUNT(w \mid w \in a \wedge w \notin b) + COUNT(w \mid w \in b \wedge \notin a)]$

To measure the total difference of the network at a specific time, all the *diff()* values from all the nodes in the network must be counted. Equation 7 describes the total difference in the network at time $t_m(TD_m)$ and n represents all the nodes in the network.

(7) $TD_m = \sum diff_n(\ )$

In each simulation the TD_m value was calculated at every determined unit of time. So at the end of each simulation, there is a group of TD_m values. These values were used to calculate an average value *(AD)* showed in Equation 8. where *m* represents all *diff()* calculations done in the simulation, and *k* represents the number of times the *diff()* function was calculated. *AD* becomes the second metric used in the simulations.

(8) $AD = (\sum TD_m)/k$

5.2 Energy Model

Energy is important because lots of network aspects depend on it. The metric used to classify nodes, the transmission range, the used energy in a message, and the method used to decide weather a message is received or not are all important aspects that depend on the energy concept. Let $OTRPTD_u$ be the Optimal Transmission Reception Power for node *u.* In other words, $OTRP_u$ is the value that is used to decide if a transmission is received or not. Let RE_{ut} be the power density with which a transmission *t* is received in *u.* Basically, when $RETD_{ut} > OTRP_u$, *t* is received successfully, *t* will otherwise not be received. In the simulation model, $OTRP_n$ has the same value for all the nodes and will be considered as *OTRP* from this point forward.

In the energy model, RE_{ut} depends on the transmission distance and energy with which neighbor *v* transmits the message. Let TE_{vt} be the transmission energy that node *v* used for transmission t, and let r_{vu} be the distance from node *v* to *u* at the time of transmission. The power density with which node *u* receives node *v's* transmission is given by Equation 9 (Tomasi, 1996).

(9) $RE_{ut} = TE_{vt} / (4 * \pi * r\ v_u^2)$

With respect to message transmission, there are two modules that interact: the node module and the network module. The node module creates the message and defines TE_{vt} to be used for transmission. Using TE_{vt} and *OTRP,* the network module can calculate the maximum radius of the transmission, and therefore identify the nodes that are influenced by the transmission. Let r_t be the maximum radio of transmission given by Equation 10. After the rt is calculated, the RE_{nt} for all the *n* nodes that were influenced is calculated using Equation 9 on each node. All of the above calculations are made based on (Tomasi, 1996).

(10) $r_t = sqrt\ (\ TE_{vt} / (4 * \pi * OTRP)\ )$

5.3 Link Quality Model

In the simulation, link quality is considered to be the energy of transmission. That is, the link quality for a neighbor is represented by the energy needed to send a message to that neighbor. Given that the energy used to send a message to a neighbor can intuitively be considered the effort that the local node has to endure to successfully transmit that message, the energy of transmission is a usable metric for link quality. The neighbor that is closest will be the one that needs less energy of transmission, and the one that is the farthest needs more energy to be reached. So the smaller values are considered to be the best quality links, as opposed to the larger values that represent links that are far away. The link quality calculation is described in Equation 11, where LQ_{uv} is the link quality that u has of *v* $(LQ_{uv} = TE_{ut})$. Remember that transmission energy depends solely on node position; no obstacle interference or noise interference values are considered. In general, each time a local node *u* receives a messages from *v* it calculates LQ_{uv}.

(11) $LQ_{uv} = (OTRP * TE_{vt}) / RE_{ut}$

5.4 Transmission Model

Not all wireless transmission environments are the same. Individual characteristics like maximum range, power use, and bit rate depend mostly on signal frequency. To specify the transmission characteristics, the model requires the maximum range of transmission (r_t), power needed to transmit a distance of r_t for one second *(ES),* and bit rate *(BS).* As stated before, the transmission model is based on Blue-Tooth 2.0 values. Equations 12 and 13 show how the simulator calculates *OTRP* and the maximum energy necessary to transmit one bit MAX_B.

(12) $MAX_B = ES / BS$

(13) $OTRP = MAX_B / (4 * \pi * r_{t2})$

5.5 Additional Simulator Aspects

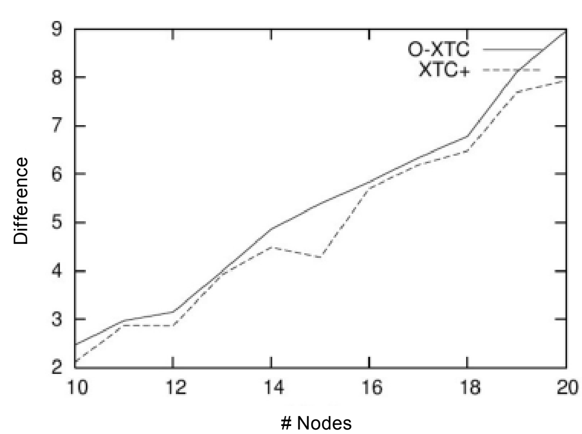
Considering that the main objective of this simulator was to provide a proof of concept, the decision was made to develop it as simply as possible. There are two characteristics that the simulator does not consider inside its simulations. These characteristics might render behavior that moves away from reality; however, it can give insight into problems with the models that can be solved before developing a real prototype.

The simulator does not implement an interference model. This basically means that nodes that are in close proximity can receive messages simultaneously from different sources. Additionally, time in the simulator was not modeled as a discrete variable. However, the simulator was implemented in Java, and therefore it does have the default behavior of its threads with respect to simultaneous events.

5.6 Simulation Process & Results

Each simulation is a group of nodes that have the same velocity range and mobility model (Random Walk Mobility Model), but in general move in different directions, different speeds and different initialization points. The simulated area is of 200 mts2, and each simulation runs for 5 minutes. The transmission characteristics of the simulations are very similar to Blue-Tooth theoretical values: a range of 50 Mts with 100 mW of power spent per second, and a bit rate of 0.8 Mbs. Additionally, all the nodes have a velocity within a range of 5m/s to 10m/s. Finally, the time for each *O-XTC* phase is 300 ms and the time for the M_2 interval is 300 ms. A total of 10 experiments were run for *XTC+* and for *O-XTC.* The number of nodes are modified from 10 to 20 and energy and accuracy are measured. *O-XTC's* synchronization is implemented using a wait period that involved all the network nodes. In other words, all the network nodes finish each phase for the algorithm to continue execution, in this way making sure the phases are synchronized.

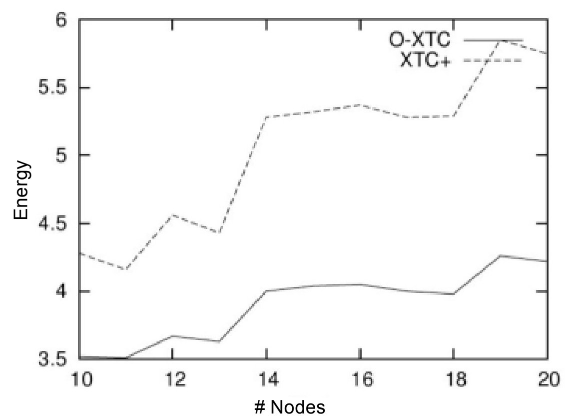
Figure 7. Accuracy in models



Figures 7 and 8 show that *O-XTC* can render a relatively better network representation than its counterpart. Let the reader be reminded that Figure 7 shows a situation in which the velocity of the nodes range from 5m/s - 10m/s, a relatively slow simulation to portray the true differences between the two models. Figure 9 shows the behavior of the two models in a situation where velocity ranges from 20m/s - 25m/s in a high density situation (14-20 nodes). It is here where the true difference between the two models is visualized. With a network that presents low variability, the models have lots of time to calculate a representation, so there will not be a great difference between them in terms of accuracy. But as variability increases, the time in which the representation is calculated becomes important and the model that requires less execution time will be the one that renders the best topology. In Figure 9, *XTC+* calculates a topology that is superior to that of *O-XTC*.

Figure 8 describes XTC+ as an energy-hungry model, and *O-XTC* as one that optimizes the use of energy. Be aware, however, that Figure 8 can be misleading in the sense that it describes an *O-XTC* model that is synchronized using methods that, to the best of our knowledge, cannot be implemented in real situations. At the same time, when the environment variability increases significantly, it is *XTC+* that renders a better topology compared with *O-XTC*. *XTC+* may be used in extreme situations where it is crucial to have a reliable communication framework.

Figure 8. Energy use in models



Conclusions

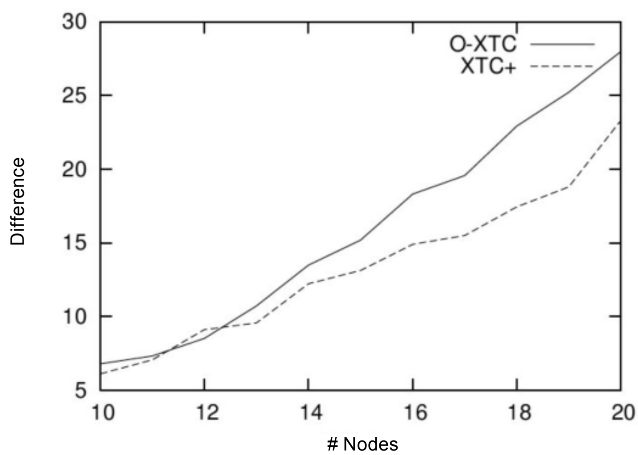
Based on the *IV* described in the change model, and comparing the two models by equaling their *IV,* it is seen that O-XTC has the advantage because it uses less messages and manages to get the same results. This conclusion is given keeping in mind that the comparison was made with an O-XTC that was missing the synchronization mechanism. Knowing the possible effort that O-XTC might have to do to implement such a mechanism, XTC+ is still a competitive model when compared to O-XTC.

Considering the results of the simulations done with relatively little variability, it is seen that O-XTC performs a great deal better than XTC+ with respect to energy usage. This is consistent with what was predicted by the change model. Moreover, the rendered topologies of the two models are very similar, which is also consistent with the change model.

On the other hand, when variability increases considerably, XTC+ can calculate topologies that are more accurate than O-XTC, but XTC+ still utilizes more energy than O-XTC. It could be possible to use XTC+ in a situation where there is a traffic spike, where the network increases its total energy usage for a moment, but goes back to the original topology control mechanism once the spike has passed. As with the change model analysis, the simulations were carried out with an O-XTC that assumed that synchronicity and the comparison can change once the mechanism is implemented.

Considering what has been proposed in this paper, XTC+ is a plausible option for a topology control mechanism in MANETs. More work must be done to decrease the message count and maintain the topology accuracy.

Figure 9. Energy use in models



Future Work

The real saving capabilities of the algorithm are not expressed in this paper because the analysis is based on the energy spent by the models, but does not concentrate on the energy saved when using the calculated topology. This saved energy must be, at least, as much as the energy used to calculate the topology. If not, there is no real point in implementing a topology control algorithm. There is no real measure of how much energy is being saved in the network, and therefore it is uncertain if the algorithm can be utilized for MANETs. Future work consists in developing a metric by which the real saving capabilities of a model can be measured, thus increasing the effectiveness of D-TCM research.

An O-XTC that is missing a synchronization mechanism is mentioned in the article. Future work consists of providing the O-XTC with a synchronization mechanism, or redesigning it in such a way that it does away with this need. That any change in the O-XTC increases the difference with the XTC algorithm must be kept in mind.

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