Link Level Design Issues for IP based Multi–Hop Communication Systems

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Abstract

In this paper we outline our future research activities in the area of wireless multi–hop communication systems. Our focus is on the link level design issues for IP based multi–hop communication systems using code division multiple access with pseudo–noise spreading sequences. We employ pseudo noise sequences to keep the signalling overhead low. In particular, we report on our initial design considerations and evaluations of a low complexity power control mechanism for multi–hop CDMA systems. Our *Interference controlled* transmit power control relies on pilot tone transmissions and adjusts the power based on the interference levels measured from the pilot tones. A rule derived from the Cocktail Party problem is used to set the transmit power level. Our preliminary simulation results indicate that our initial design increases the capacity in the center of the network, which is most frequently traversed. Also, our design reduces the overall consumed power. On the downside our design reduces the overall capacity in the network. In our ongoing work we study the trade–offs between capacity and consumed power as well as the areas of increased/reduced capacity/connectivity and their impact on the overall QoS provided by the network in more detail and refine our design to achieve optimal trade–offs.

Keywords: CDMA, MAC Protocol Design, Multi–hop Networks, Power Control, Pseudo–noise Spreading Sequences.

I. INTRODUCTION

Mobile multi–hop[1] enabled wireless terminals can dynamically form a network, where the network infrastructure is missing, incomplete, or inadequate. Due of the potential ease of deployment, there are a many interesting deployment scenarios for multi–hop networks. Example scenarios include disaster management, military operations, or in general scenarios where a group of people wish to communicate with each other [1]. In multi–hop networks communication is possible in a *point–to–point* fashion between wireless terminals. If the coverage of two terminals is too small to reach each other, the terminals communicate by *hopping* over neighboring terminals. Multi–hopping enables two distant terminals to communicate with each other and has also the potential to save energy. Achieving efficient bandwidth usage in an ad hoc network by coordinating the transmissions of the distributed wireless terminals through signalling is very difficult if not impossible. We advocate therefore the use of CDMA, which supports uncoordinated transmissions [2] in a bandwidth efficient manner. Generally, the performance of CDMA is interference limited. Power control is typically employed to reduce the interference and thus increase the performance. Power control in multi-hop networks, however, poses unique and novel challenges, which we outline next.

II. PROBLEM DESCRIPTION: POWER CONTROL IN MULTI–HOP CDMA NETWORKS

In a CDMA system multiple transmitters use the same bandwidth at the same time to send their information to one or multiple receivers. Due to the attenuation, a given terminal receives higher power levels from transmitting terminals that are close by than from transmitting terminals that are far away, which is known as the *near–far effect*. The near–far effect plays a crucial role in multi–user CDMA systems, which are interference limited. To overcome the changing signal strength, power control entities are implemented in the transmitters. These entities are commonly referred to as **T**ransmitter **P**ower **C**ontrol (TPC). For cellular CDMA mobile communications systems the TPC adjusts the transmission power P_t at the sender–side to ensure that all signals arrive at the receiver with the same power level P_r. Generally, the lower the power level of a given terminal, the larger the number of supported terminals in a CDMA cell. TPCs typically are implemented either (i) an open loop power control, or (ii) a closed loop power control, or a combination thereof. Some wireless CDMA communication systems also have an outer loop power control, such as IS–95 [3]. The main goal of the TPC in cellular systems is to adjust the power of each transmitting node such that the received signals are equal in power. The open loop power control, for instance, achieves this by measuring the SIR of the incoming signals and adjusting the transmission power to meet the desired SIR.

The TPC is also a very important — and not yet well understood — entity in multi–hop CDMA systems. The design of the TPC for multi–hop CDMA systems is significantly more complex than the design for cellular CDMA systems. This is because ad hoc networks are lacking the structure of cellular networks. In cellular networks all communication is organized in downlink (base station to mobile terminal) and uplink (mobile terminal to base station) communication. There is no direct communication between two mobile terminals, i.e., if two mobile terminals wish to communicate with each other, the communication is relayed by the base station. This structuring of the communication with a central entity (base station) provides for central coordination and inherent fairness in the power allocation. In ad hoc networks on the other hand, two mobile terminals communicate directly with each other, without any relaying by a central entity. In this unstructured scenario each receiver tells the sender that it is communication with

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[1] The terms multi–hop and ad hoc are used interchangeably in this document.

to transmit with the power level that ensures proper reception. Each receiver thus to controls its corresponding sender in a selfish manner, without any central control or coordination. The absence of a central coordination (with overall knowledge), however, may lead to an instable situation in an ad hoc cluster if multiple receivers want to control the transmitting power of the related node. To overcome the problem of missing knowledge signalling between nodes can be used (see for instance [4]). Signalling, however, consumes bandwidth and because of the frequent changes in an ad hoc network the signalling has to be repeated frequently. In contrast to employing orthogonal CDMA codes for transmission (see for instance [5]), we advocate the use of pseudo–noise sequences. This allows us to build a low cost node and we are taken advantage of the possibility to use the interference level for our power control adjustment.

III. SOLUTION APPROACH: INTERFERENCE CONTROLLED TPC

Power control is generally used to increase the capacity in a network. When the complete knowledge of all transmitting powers is missing, some signaling among the nodes is necessary to exchange at least a local knowledge. However, an overwhelming amount signaling would decrease the already scarce bandwidth of wireless multi-hop networks. Therefore we designed an *Interference controlled TPC*. This TPC approach is designed for low cost terminals or nodes, which can only run low-complexity algorithms and mechanisms, e.g., nodes in sensor networks. The Interference controlled TPC works as follows. Each wireless terminal listen to pilot tones of the neighboring terminals. The pilot tones are transmitted with the maximum transmit power $P_{\max}$. The pilot tone contains information about the wireless terminal such as an ID, the mobility and power class, etc., and the probability to send within the next time period. Furthermore the pilot tone contains the maximum interference value I_{MAX}. This is either (i) the interference level I_{local} experienced by the terminal, or (i) the interference level of its neighbor if the neighbor's level is larger. In our initial design we adjust the TPC by means of the local interference level and I_{MAX}. We follow a simple rule known from the *Cocktail Party Problem*. For fairness we ask nodes with low interference (at the edge of the party room) to send with low transmission power, simultaneously terminals with high interference (in the middle of the room) has to use higher transmission powers. Thus, the higher the interference level the higher the transmitting power. Each node adjust its transmission power by calculating

$$P_t = P_{\max} \cdot \sqrt[\alpha]{\frac{I_{local}}{I_{MAX}}}, \tag{1}$$

where α is a tuning parameter that can be optimized. For our initial simulations we set $\alpha = 2$. Note that in case the local interference is the highest interference level the node transmits with maximum power.

IV. SIMULATION MODEL FOR CDMA BASED MULTI–HOP COMMUNICATION SYSTEM

For our initial simulations we consider J wireless terminals that want to communicate with each other using single or multiple hops to reach the target terminal. The wireless terminals are distributed over a plain rectangular area (80 m by 120 m). Each wireless terminal $j,\ j = 1, \ldots, J$, is identified by its unique Cartesian coordinates $(x_j,\ y_j)$ and transmits with power $P_t(j) \le P_{\max} = 200$ mW[2] In the following we outline the wireless link model, the power control entity, and the calculation of the bit and packet error probability for CDMA links.

A. Wireless Link Model

For our initial simulations we use the free space propagation model to determine the received signal strength at the receiving terminal under the assumption that there is only one line of sight path between the sending terminal and the receiving terminal. Then, the strength of the received signal P_r depends on the transmitted power P_t, the distance d between sender and receiver, the antenna gain of sender and receiver, G_s and G_r, the wavelength λ, and the path loss L, and is given by [6], [7]

$$P_r(j) = \frac{P_t G_t G_r \lambda^2}{(4\pi d)^2 L}. \tag{2}$$

Note that in this free space equation the received power declines with the square of the distance. In the following calculations we set $\frac{G_t G_r \lambda^2}{(4\pi)^2 L} = -30$ dB.

B. Bit Error Probability in CDMA Networks

The classical expression for the bit error probability of a DS CDMA system with pseudo–noise sequences assuming uncoded **B**inary **P**hase **S**hift **K**eying (*BPSK*) modulation and considering additive white Gaussian noise with power spectral density I_0 and energy per bit E_b is given by

$$p^{BPSK}_{biterror} = Q\left(\sqrt{2 \cdot SIR}\right) = Q\left(\sqrt{\frac{2 \cdot E_b}{I_0}}\right), \tag{3}$$

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[2] The value for $P_{max} = 200$ mW is motivated by the fact that this is the maximum power for the 5 GHz ISM band in Europe.

where $Q(x)$ is the complementary error function defined as

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2} dt. \tag{4}$$

This expression assumes that all wireless transmissions arrive chip synchronously but phase asynchronously.

The energy per bit E_b is obtained by dividing the signal power P_r received at terminal k from terminal i by the data rate R_i

$$E_b = \frac{P_r}{R_i}. \tag{5}$$

To calculate the power spectral density I_0 for terminal k receiving a signal from terminal i all active wireless terminals $j = 1, \ldots J,\ j \neq i$, have to be taken into consideration, i.e.,

$$I_0(k) = \frac{\sum_{j=1 \ldots J, j \neq i} P_r(j)}{W_{SS}}, \tag{6}$$

where W_{SS} is the bandwidth.

Using Equations 3, 5, and 6 we obtain

$$p_{biterror} = Q\left(\sqrt{\frac{2 \cdot \frac{P_r(k)}{R}}{\frac{\sum_{j=1 \ldots J, j \neq i} P_r(j)}{W_{SS}}}}\right) = Q\left(\sqrt{\frac{2 \cdot P_r(k) \cdot G}{\sum_{j=1 \ldots J, j \neq i} P_r(j)}}\right), \tag{7}$$

where G is the spreading factor. In summary, the bit error rate $p_{biterror}$ at terminal k for a transmission from terminal i depends on the received interference level from all other terminals that are transmitting at the same time. In the considered free space propagation model the received interference depends on the location/topology of the wireless terminals.

C. *Packet Error Probability in CDMA networks*

Given the bit error probabilities, the **P**acket **E**rror **P**robability (*PEP*) for a packet data unit of length L_{PDU} [bit] for uncoded transmission is given by

$$p_{pkterror}(L_{PDU}, k) = 1 - (1 - p_{biterror}(k))^{L_{PDU}}. \tag{8}$$

D. *Capacity for a CDMA Link*

We define the nominal capacity of a CDMA link as

$$C = 1 - p_{pkterror}(L_{PDU}, k) \tag{9}$$

V. INITIAL SIMULATION RESULTS

In our first simulations we investigate some basic well-know topologies (Chain, Bridge, Manhattan). We compare our *Interference controlled TPC* approach with an approach which always uses the highest transmission power. We assume that all wireless terminals have always some data to send. For the illustration of the multi–hop network we use our own visualization tool for multi–hop networks (ViTAN) [8]. The tool depicts the wireless terminals and their coverage area depending on the transmission power. In case the terminals can reach each other, a weighted and directed edge is drawn between two nodes. The weight (represented by the line thickness and a color code in the plots) of each edge represents its capacity C. For illustration purposes we use values from $0 - 8$ to represent the capacity (where 1 (11% of maximum capacity) is a bad and 8 (100% of maximum capacity) is a very good connection). Note, that the capacity of a connection between two wireless terminals is not symmetrically. This is due to the different interference levels.

In the following we provide figures to illustrate the effect of power control in the classical scenarios Chain (Figs. 1 and 2), Manhattan with 16 wireless terminals (Figs. 3 and 4). For each scenario we compare the operation with power control (using the interference controlled TPC) with the operation without power control (where each terminal transmits with the maximum power). The mean values of the power used by the wireless terminals are summarized in Table I.

We observe from the Chain scenario that the power control increases the capacity in the center of the chain, which is typically the part of the network that is most frequently traversed. We also observe that the power control reduces the capacity for some hops towards the fringes of the network. However, the overall average power consumption with power control is 90 % of the consumption without power control.

The observations for the Manhattan scenario are similar, with the hops in the center of the network benefitting from the power control with higher capacity whereas the capacity of some hops towards the edges of the network is reduced. Assuming that every terminal communicates at times with every other terminal, the center of the network has to carry the most traffic. Thus increasing the capacity in the center improves everyones experienced QoS and is beneficial to the network overall. In addition, the overall average power consumption is reduced to 87% by the power control, resulting in longer battery life.

TABLE I

POWER CONSUMPTION FOR CLASSICAL SCENARIO.

scenario	without power control	with power control
chain	100%	90%
bridge	100%	87%
Manhattan 16 wireless terminals	100%	87%
Manhattan 22 wireless terminals	100%	87%

VI. CONCLUSION

By simulations we have demonstrated that our low complexity approach for power control gives favorable results in terms of power consumption and capacity for the classical topologies (e.g., Chain and Manhattan). These topologies may be encountered in sensor networks, where the very low cost wireless terminals can only implement low complexity mechanisms.

VII. OUTLOOK

In our future work we are investigating more general scenarios such as a Random Placement scenario. Initially we fix the number of wireless terminals at 22 in this scenario. Figure 5 (without power control) and Figure 6 (with power control) depict one of such random topologies. By averaging over 10^6 independent randomly chosen topologies we obtain estimates for the consumed power and the connectivity level in the network, which are reported in Table II for different spreading gains G. The connectivity level is the fraction of all valid connections (a chain of links with at least quality level 1) and all connections $(J \cdot (J - 1))$. Note, the connectivity level for all prior examples was 100%. The design rule is to achieve a high degree of connectivity while minimizing the power consumption. This very first simulation indicates that the power consumption is significantly reduced by our approach. However, the connectivity is reduced as well. We will investigate these effects in more detail and refine our approach to achieve optimal trade-offs between a high degree of connectivity level of and low power consumption.

TABLE II

POWER CONSUMPTION AND CONNECTIVITY LEVEL FOR RANDOM PLACEMENT SCENARIO WITH 22 WIRELESS TERMINALS.

spreading gain	without power control		with power control	
	connectivity level [%]	power [%]	connectivity level [%]	power [%]
8	5.62	100	5.59	46.4
16	16.50	100	14.18	46.4
24	34.67	100	25.72	46.4
32	52.82	100	37.93	46.4
48	73.53	100	56.72	45.75
64	81.78	100	67.50	44.70

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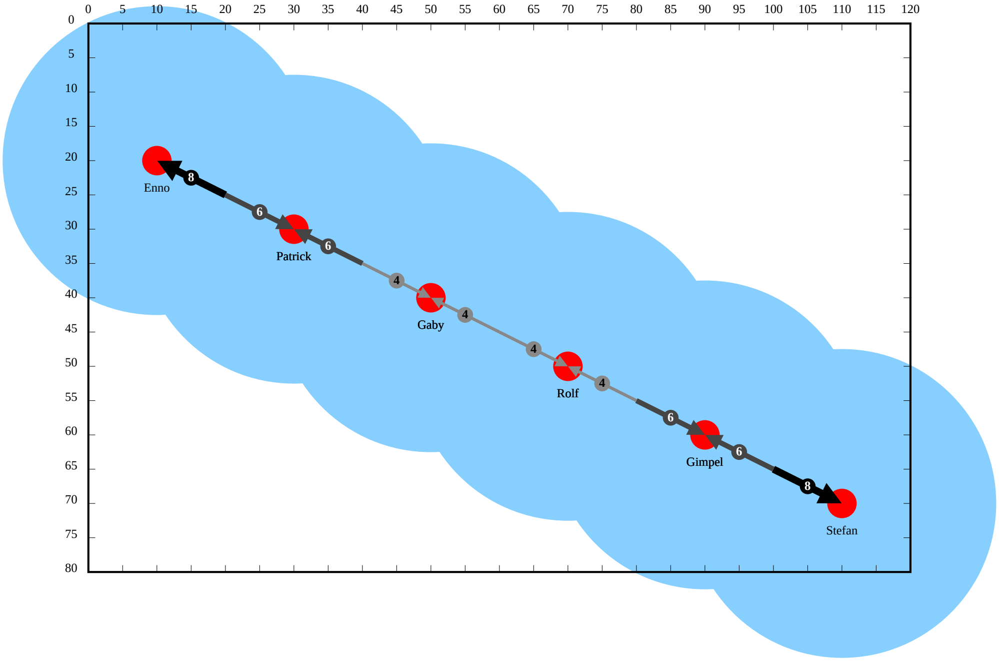

Fig. 1

Chain scenario without power control. Six terminals located on a straight line communicate with each other on a rectangular 120 m by 80 m area.

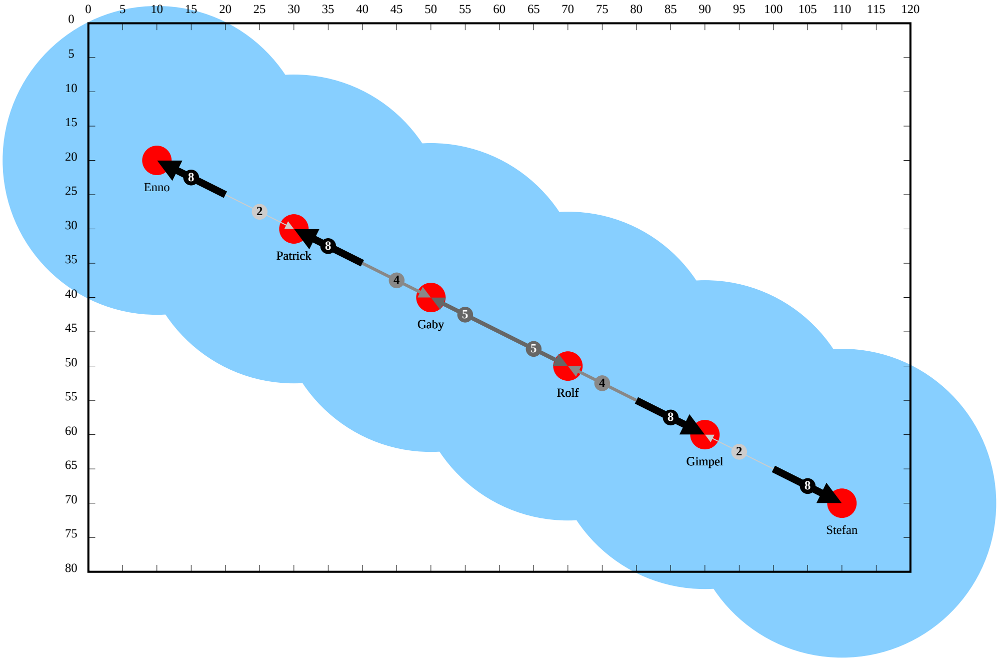

Fig. 2

Chain scenario with power control. The interference controlled TPC gives higher link capacities in the center of the chain, which is frequently traversed.

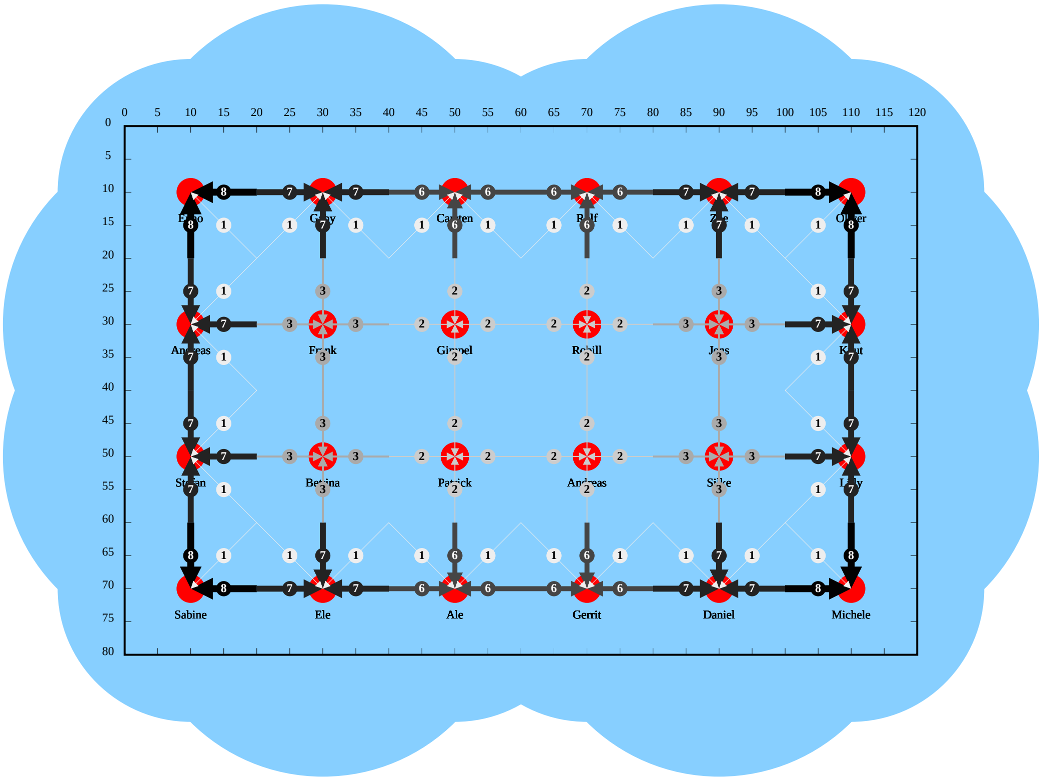

Fig. 3
MANHATTAN SCENARIO (16 WIRELESS TERMINALS) WITHOUT POWER CONTROL.

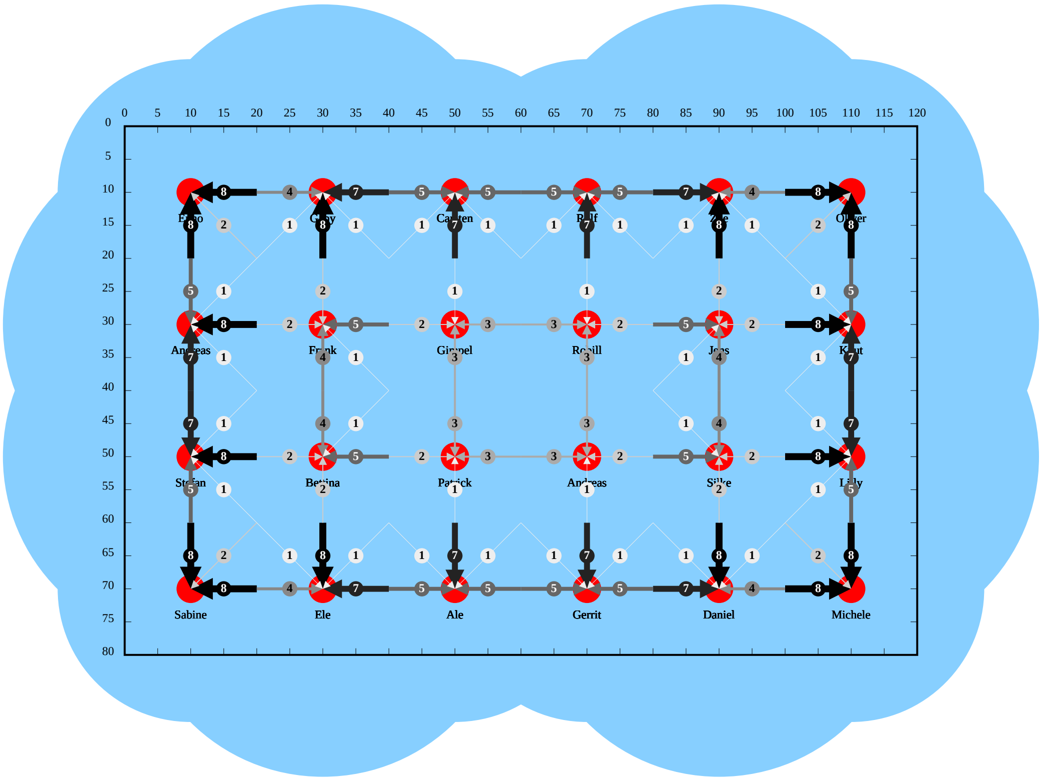

Fig. 4
MANHATTAN SCENARIO (16 WIRELESS TERMINALS) WITH POWER CONTROL.

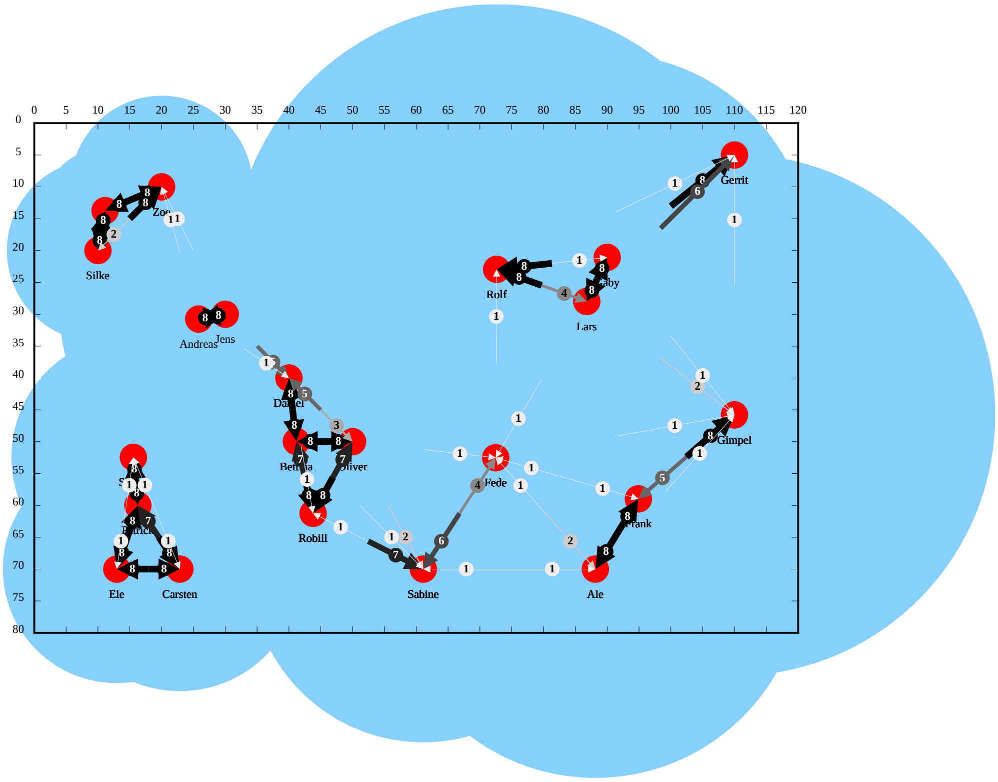

Fig. 5

RANDOMLY PLACED WIRELESS NODES WITHOUT POWER CONTROL.

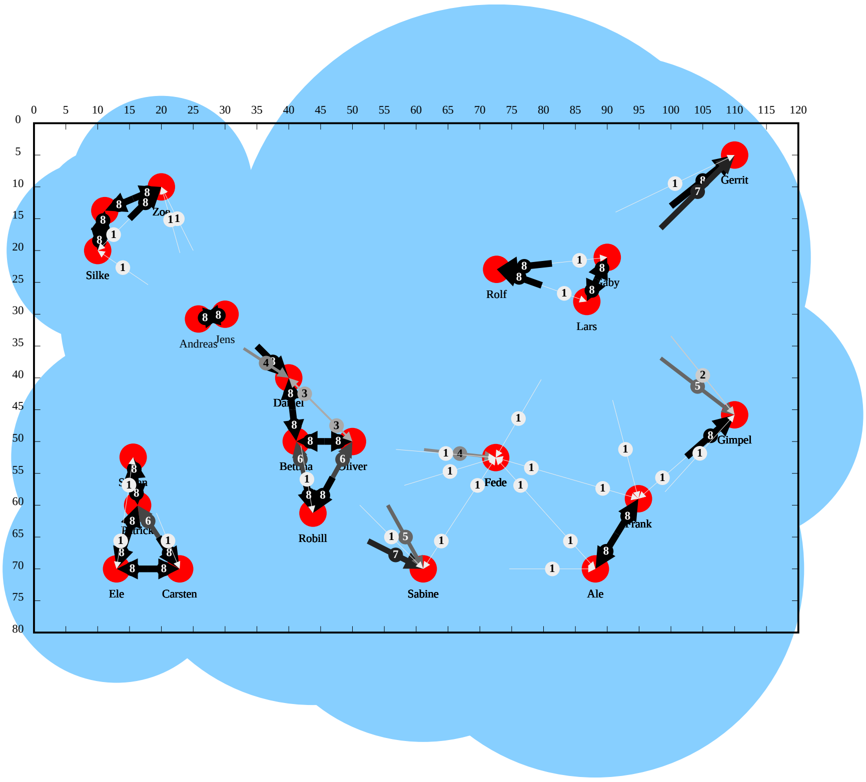

Fig. 6

RANDOMLY PLACED WIRELESS NODES WITH POWER CONTROL.