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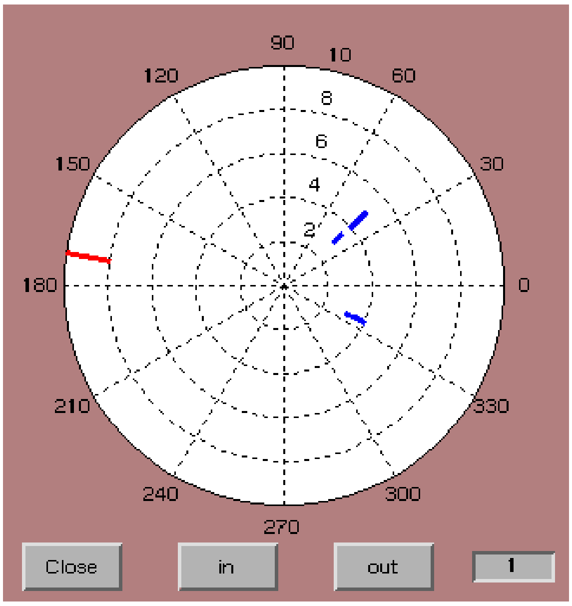
Simulation Platform for Multifunction RF-Systems.

Concept Description, Design Principles and Development of v0.1.



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Report title

Simulation Platform for Multifunction RF-Systems.
Concept Description, Design Principles and Development of v0.1.

Abstract (not more than 200 words)

Mobile and flexible nodes are key features of a future Network Centric Warfare concept. Important factors when operating an efficient and robust network will be access to secure communication channels, reliable sensor information, and a possibility to dynamically change the roles allocated to different nodes within the network. Microwave-based reconfigurable multifunction systems, capable of performing different functions regarding e.g. radar, electronic warfare, communications and navigation/positioning will be cost-effective alternatives to dedicated systems. If factors such as weight, volume, radar cross section, cooling etc. are considered, the advantages are even bigger, especially for small, mobile platforms.

In this report, the pros and cons of multifunction systems are discussed from a tactical/operational perspective as well as a technical and functionality perspective. An example of a concept for a multifunction front-end system is also presented.

A simulation model for a multifunction system has been developed in a first version. The tool is implemented in Matlab 6, and is capable of handling a test scenario where jamming and communication functions are to be maintained. As a basis for further development, general design principles for such a simulator have been compiled. These cover objectives of simulation, the structure of the model and implementation aspects. The work described in this report has been funded within the *Strategic research cores*.

Keywords

System simulator, multifunction system, array antenna, radar, electronic warfare, communications

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Simuleringsplattform för ett multifunktionssystem.
Konceptbeskrivning, uppbyggnadsprinciper och utveckling av v0.1.

Sammanfattning (högst 200 ord)

Hög mobilitet och flexibilitet är två grundkrav som kommer att ställas på många noder i det framtida nätverksbaserade försvaret. Krav på tillförlitlig sensorinformation, kommunikationskanaler med hög tillgänglighet och säkerhet, samt möjlighet att dynamiskt förändra rollfördelningen mellan olika noder är nödvändiga komponenter för att åstadkomma ett effektivt och robust nätverk. Mikrovågsbaserade, rekonfigurerbara multifunktionssystem, kapabla att upprätthålla olika funktioner för exempelvis spaning, varning, störinsats, kommunikation och navigering/positionering utgör i detta perspektiv ett kostnadseffektivt alternativ till dedicerade systemlösningar. Om faktorer som volym, vikt, radarmålyta, kylbehov mm vägs in torde fördelarna vara ännu större speciellt för små, mobila noder.

I denna rapport diskuteras för- och nackdelar med ett mikrovågsbaserat multifunktionssystem ur såväl ett taktiskt/operativt perspektiv som ett tekniskt- och funktionalitetsperspektiv. Ett exempel på tekniskt koncept för att realisera en front-end i ett multifunktionssystem presenteras dessutom översiktligt.

En modell för att simulera ett multifunktionssystem har utvecklats i en första version. Det framtagna verktyget är skrivet i Matlab 6 och hanterar för närvarande ett testscenario där störnings- och kommunikationsfunktioner skall upprätthållas. Som en bas för fortsatt utveckling av detta simuleringsverktyg har generella uppbyggnadsprinciper för simulatorn tagits fram. Dessa omfattar frågeställningar rörande simuleringsmål, modellstruktur och implementeringsaspekter. Arbetet har bedrivits under rubriken *strategiska forskningskärnor*.

Nyckelord

Systemsimulator, multifunktionssystem, gruppantenn, radar, telekrig, kommunikation

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Content

1. Introduction

This report describes the work performed in the first year of a project focused at developing a simulation tool for a broadband multifunctional microwave RF-system. The project has been funded as a so called *Strategic research core* within the Swedish armed forces' R&T structure.

Broadband, multifunctional microwave RF-systems are judged to have considerable potential for cost-effective implementation of important functions related to e.g. radar, electronic warfare and communication in a large spectrum of military platforms. By developing new reconfigurable architectures and flexible software, a possibility of maintaining several functions in the areas mentioned above in one single system, and with one single RF front-end, will be created. This is expected to give substantial advantages concerning for example cost, performance, weight, total power consumption and radar cross section for a given platform.

Developing a flexible microwave based multifunction system is a very complex task where several, sometimes conflicting, requirements are to be satisfied. Using a computer based simulation tool is one way of assessing the overall performance of a given system under different conditions. Such a tool will also give the user a possibility to efficiently analyze the impact of new technical developments from a system- and user-perspective. This will also create a possibility to achieve a clear feedback from technical conditions to the influence on tactical behaviour in a given scenario, and vice versa.

The overall objective of the project reported here is to develop a simulation tool, capable of modelling a broadband microwave multifunction system. The goal was not to initially specify and develop a system for all conceivable RF-functions, but rather to start with a few functions and gradually expand the complexity of both the simulation tool and the description of the system to be simulated. Especially, during the first year of the project a first version (v0.1) of the simulation tool should be developed to acquire experience. This development started before the system description or design principles was completed. The reason for this was that the hands-on experience gained during the development of v0.1 can be used both when defining the design principles and when developing new versions of the simulation tool.

The report can roughly be divided into three separate parts described below.

- Overview and brief description of a multifunction RF-system concept. The objective of this part of the report is to discuss the tactical/operational as well as functional aspects of RF based systems in general terms, and also give indication on the advantages (and disadvantages) of having a single system performing several functions. This part will also serve as a system description basis for the development of the simulation tool.

- A summary of the design principles that should be used when developing the simulation tool. In this part a roadmap for the simulator development is discussed, based on the simulation objectives. Different ways to handle a number of aspects, objects and events are covered.

- A description of the first version (v0.1) of the simulator is given. The scenario and the different models used are described, as well as the input/output and graphical user interface. A summary of the most important assumptions and simplifications in the simulation tool is also given.

Each part of the report corresponds to a work package of the project, and can be regarded as a condensed output of the work performed in that work package. Of course, the main result of the work is the competence and experience gained by the participants, and that will be further exploited during the completion of the project. Another, more tangible result is the code for the simulation tool.

2. Multifunction systems

2.1. What is a multifunction system?

Active phased array antennas are receiving a great deal of attention for their use in both radar and electronic warfare (EW) systems. Principles of phased arrays have been applied in radar since World War II. However they became operational in the late seventies. They are used to achieve high scanning rate in order to operate simultaneously against several threats. Advances in monolithic microwave integrated circuits (MMICs) and high-density microwave packaging (HDMP) technologies have made possible the realization of phased arrays, containing many hundreds of T/R (transmit/receive) modules. Phased arrays can be of shipboard, land-based or airborne versions. One of the challenges facing the military platforms today is to increase the number of onboard RF functions, including radar, electronic warfare and communication, without degrading their stealth capabilities. All these functions are today being performed by separate systems.

The long-term vision of radar, electronic warfare and communication sharing a common antenna has a long way to go. However, several programs [1-3] on multifunction radar show that all the functions (search, tracking, identification, etc) previously performed by individual and dedicated radars, can be performed using a single system. The considerable knowledge and experience that have been gained during the development of multifunction radars can be seen as the vehicle to address the basic requirements and the technological challenges of a single RF front-end shared by communication, radar and electronic warfare functions, in this report called a *MultiFunction Antenna* (MFA). Some benefits of such a system are reduction of platform radar signature, low cost, low weight and the possibility for small platforms such as Unmanned Aerial Vehicles (UAV) to perform multiple tasks. Such a system does not only require a broadband behaviour in terms of apertures, T/R modules, beamforming and beamscanning, it also requires modular and reconfigurable architectures in order to, dynamically, reconfigure the array(s) to the required function(s) and to other parameters such as effective radiated power (ERP) and beamshape. Such a system will inevitably involve compromises. This part of the report addresses the design requirements for such systems in terms of the trade-off between the different functions, keeping in mind the goal of maximizing the benefits and minimizing the penalties incurred. New component technologies and innovative beamformer architectures, which are required in order to effectively and economically designing such a system, are also briefly addressed.

An MFA is a wideband (instantaneous and multi-band) active phased array system using a single RF front-end to handle certain functions associated to radar, EW and communication. The system aperture can be of shared-aperture type or consist of several sub-apertures optimised for a specific frequency band or system function. Figure 1 shows a schematic diagram of a multifunction active phased array system.

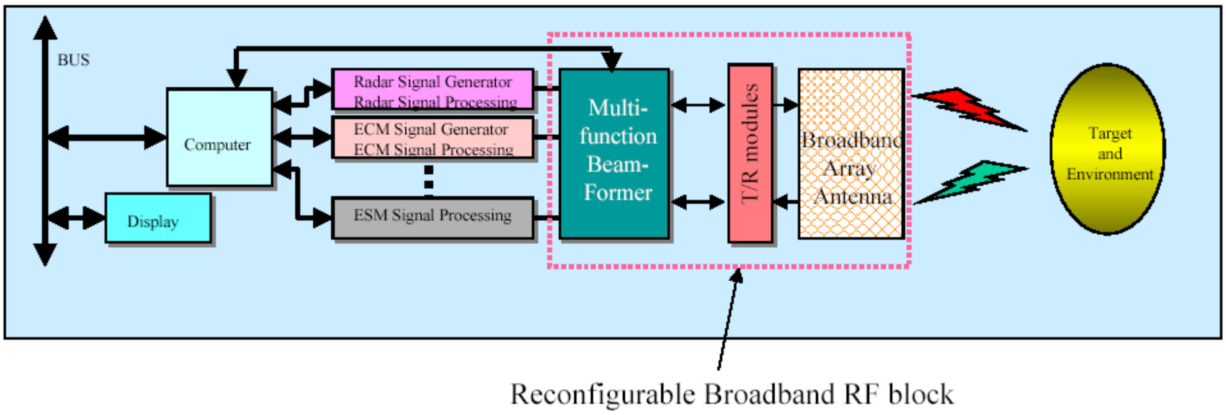

Figure 1 Schematic diagram for a multifunction active phased array system

Compared to the traditional solution where the radar, EW and communication functions are realised using separate RF front-ends, the weight, price and radar cross section (RCS) can be reduced significantly by using an active multifunction phased array based on a single RF front-end. This can be very important for platforms with limited space and power such as a UAV. The survivability of a platform could be enhanced due to the possibility of RCS reduction and functional cooperation between platforms. A broad-band, flexible, reconfigurable and reprogrammable system could also be configured according to several standards, something that would be very interesting especially considering interoperability aspects of international operations

2.2. Tactical and operational aspects of multifunction RF systems

2.2.1. General

As an introduction to the discussion of the technical requirements we will in this section discuss the tactical and operational aspects of multifunction RF-systems. We start with a short but broad review of the radio- and radar-functions that are used in sea, air and ground platforms. The starting point for our discussion is the capacities and requirements for the current Swedish platforms. These capacities and requirements will possibly change along with the establishment of concepts such as Network Centric Warfare (NCW) and autonomous platforms. Nevertheless, we emphasize the necessity to take advantage of tactical experiences from existing systems. Several factors will most likely be common for current and future platforms. Some examples are performance requirements and course of events in air-to-air or air-to-ground efforts. Furthermore, many parts of current systems are highly qualified and will remain at the technical leading edge for many years. Related to the current capacities and requirements, we discuss the new requirements that are anticipated according to the Swedish Armed Forces Perspective Planning.

2.2.2. Air

The tasks for airborne platforms are divided into air-to-air, air-to-ground and reconnaissance. In the JA/AJS-37 (VIGGEN) system these tasks are executed by different platforms, whereas the JAS-39 (GRIPEN) system allows change between the tasks (or modes) in one platform. The functional requirements for each task are however similar for both systems. In the following we will treat the radar functions for the air-to-air task separate form the air-to-ground/reconnaissance tasks.

The radar function in the air-to-air mode demands a target detection range in parity with the weapon system range. Measurement of relative speed by Moving Target Indication (MTI) enhances the detection and display of moving radar targets by suppressing fixed targets, such as land features and chaff. The air-to-air (A-A) radar locks onto the hostile target and is used for guidance of the air-to-air missile (AAM). An AAM equipped with radar seeker is either semi-active or active. The semi-active seeker uses radiations or reflections from the target which has been illuminated by the airplane radar. The active seeker has both a transmitter and a receiver. In the first part of its flight path, the missile is guided by information from the airplane radar. In the final phase, the missile radar takes control of the missile. For the semi-active case, the airplane radar must stay locked onto the target until the missile has reached the target. For the active case, the airplane radar can release the target at an earlier phase. The A-A radar-mode also admits a number of rapid lock-on functions, which involves programmed scanning patterns for various types of situations. Some of these situations concern localisation of friendly aircraft or aircraft in own division. The radar function in the air-to-ground (A-G) and reconnaissance mode demands ability to search for ground targets. It does not use an MTI function. A number of programmed A-G scanning patterns are used e.g. to split up a geographical search area between several aircraft in a division, or to search in a priority area. Apart from the above mentioned radar functions, also a radar altimeter is employed. The altitude is measured both by the radar altimeter and by static pressure. The radar altimeter data is displayed at altitudes lower than 200 m. For safety reasons, it is active also at higher altitudes but can be manually shut off by the pilot.

The radar warning receiver (RWR) and electronic countermeasures (ECM) are parts of the aircraft RF functions. The RWR function shall be able to detect radar transmission from all directions. The ECM function can generate two types of radar jamming: noise and deception jamming. A continuous noise jamming signal has the disadvantage of exposing the own platform for enemy anti-radiation missiles. Deception jamming (or repeater jamming) injects false information into the victim radar to deny critical information on target direction, range or a combination of these parameters.

Functions for radio communication can be divided into speech, data, link, and identification friend or foe (IFF). IFF is the system using electromagnetic transmissions to which equipment carried by friendly forces automatically responds, for example, by emitting pulses, thereby distinguishing themselves from enemy forces. Speech and data are used for tactical signals within the division, with the combat control center and with collaborating units. The link function is used for automatic update of e.g. the situation map, known targets, own position, and remaining weapons/fuel.

Future air force tasks and environments, will affect the functional requirements of the RF-systems. The development towards larger fighting range will demand early detection by own sensors or information transfer from a forward (perhaps unmanned) platform. The cooperation between manned and unmanned aircraft will require communication capacities. An increasing use of unmanned aerial vehicles (UAV:s) is anticipated. Upgraded anti-aircraft and air-to-air missile technologies will augment the requirements on the RWR- and ECM-systems. It is necessary to pay attention to the enhanced anti-aircraft capacity against small and fast targets. Low weight and small physical size will demand solutions where several functions are integrated into one system, e.g. radar search, communication, RWR and ECM. A rising importance for stealth technologies in air combat situations can result in higher demands on search and detection systems. There is a development towards flexible platforms that e.g. can change their flight characteristics for different missions. It is reasonable to expect that also the RF-functions need to be adapted for each type of mission or task. Finally, a more qualified system design of the platforms is expected, which concedes new conditions for maintenance and robustness. New aspects on maintenance and robustness will therefore be important parameters also for design of the RF-systems.

2.2.3. Sea

For the naval platforms, we consider those RF-functions that are necessary in platforms with main tasks surface attack and air-defence, and with supplementary tasks mine warfare, and undersea warfare. We choose *surface attack* and *air-defence* as main tasks, because these functions have the highest requirements on the radar functions. In the context of RF-functions a commentary on submarines is appropriate. The main sensors for the submarine is of course acoustic sensors, however there are also relatively high requirements on the radar capacity in these platforms. In particular, the RWR ability is of high importance as a complementary sensor for the submarine.

The active radar functions for surface attack missions can be divided into search, navigation, and fire control radar. The search function shall detect both surface (ships) and air targets. This function relies on high detection probability at large ranges. The search radar is also used for automatic tracking of surface targets. The tracking parameters are employed for fire control of the artillery (against surface targets). The navigation function is operated primarily in the archipelago and demand high range- and angular resolution. The navigation radar is currently separated from the search radar, though the navigation radar can deliver surface target coordinates to the ship combat control system, as a complementary function. The fire control radar for air-defence is also a separate system, which has high angular resolution both in elevation and azimuth. It is able to track and lock onto targets initiated by position/direction information from e.g. the search radar, or from its own scanning pattern programs. The target parameters from the locked-on mode are used for the fire control of the air-defence artillery.

The RWR functions can be divided into warning, search and target analysis. Usually, several of these functions are built into the same physical system. The warning function shall be able to continuously detect radar emission and give approximate bearing to the emitter, at all directions and for several wavelength bands. The priority targets are fire control radars (air, sea, or land) or airplane/missile search/track radars. The RWR search function is generally the most important (own) sensor for surface attack with surface-to-surface missiles (S-S). This function requires high detection range, similar to or larger than the missile maximum range. Target coordinates are obtained by precise target bearing information from two or more ships in own or collaborating division. The RWR target analysis is necessary for classification and identification of the target.

Hostile units practising emission control (EMCON) combined with own requirements on high weapon engagement ranges, sometimes demands the utilization of a forward active search radar e.g. on a helicopter. The helicopter will then transmit target coordinates, which are used for the ship’s S-S missile engagement.

Radio communication is used both within the division and with land and collaborating units. Also, systems for IFF are employed. Tactical signals are usually transmitted in the VHF-band. Shortwave (MF-, HF-bands) is used for communication of orders/reports with land command and control center or for other long-range communication. Currently, omni directional antennas are used for communication. A necessary balance is kept between communication-needs and EMCON.

Future naval tasks and operational environments, will affect the platform RF requirements. One example is the participation in international operations, which will demand interoperability in the communication and control functions (exchange of target data and other). Another example is the demand for self protection and continuous high safety standards for own platforms and personnel. Communication with forward search and reconnaissance UAV:s/helicopters will become necessary to minimize the exposure in unsafe areas. A stronger integration of navy and amphibious units will oblige high functionality in the communication functions. The requirement on high detection range in the search functions will increase, as the stealth technologies develop. Conceivably, bi- or multi-static radars will be needed for detection. Hostile UAV:s and missiles will become smaller and stealthier, which intensifies the demand for detection ability of air targets.

2.2.4. Land

There is a wide range of platforms used on land in military ground operations. They are often developed for specific purposes or functions. The term platform can on land mean everything from the single combat soldier to e.g. advanced combat vehicles with different weapon systems. Platforms can be stationary and mobile.

Capabilities to perform ground target engagement at close range as well as medium and long range (even beyond visual range) are essential in ground operations. Furthermore, ground operations require capabilities in air defence (surface-to-air, S-A). Other capabilities that are supporting ground target engagements are for instance surveillance, reconnaissance, and target recognition in many different terrain and weather conditions. This will usually include systems such as traditional optical (including infrared) sensors but laser, radar, and different signal intelligence systems are also used to provide the situation awareness that is needed for the mission. Sensor data fusion and sharing sensor data with other platforms are important ingredients in future network centric warfare.

The fragmented battlefield sets high demands on the capability to identify friend or foe (IFF systems) to minimize the risk for losses due to friendly fire. The capabilities for precise positioning and navigation for each single platform or warfighter will give possibilities for distributing precise target parameters to other platforms in the network and also increase the flexibility and capability for autonomous performance on the battlefield.

The capabilities for robust and secure voice and data communication with radio, RF-links, or stationary transmission lines between platforms are important to achieve the desired tempo and efficiency in ground battle operations. The capabilities to conduct, and also be protected against, electronic warfare (electronic attack, electronic support, and electronic protection) are essential. Active capabilities in this area include signal intelligence (SIGINT), electronic support measurements (ESM), and jamming (electronic counter measures). Survivability sets demands on the ability to detect treats (warning systems), take protective actions (e.g. electronic counter-counter measures, ECCM), or in the worst case capability to resist direct physical hits of different kinds without loosing essential functions. The capability to retain vital functions, or parts of these functions, can be achieved by implementing not only physical protection or robustness but also designing redundant systems or subsystems that allows graceful degradation.

New warning and countermeasure systems for combat vehicles are under development. The development in material technology makes it possible to design lighter and stealthier combat vehicles and others platforms with increased or at least sustained level of survivability.

The development of the concept of precision engagement such as precision-guided ammunition or high-velocity projectiles implies the necessity of having advanced units for fire-control or target illumination to be able to control effects of and guide long range target engagements. The possibilities to use advanced ground combat units for these kinds of tasks increases with the development in the areas of communication and information technology. At the same time, the development of unmanned platforms such as UAV and UGV (unmanned ground vehicles), sensor and tracking systems, and other new technologies e.g. fibre-optic guided missiles can provide alternatives to manned units.

New technological advances will affect the development of future tactics and combat techniques. Future technologies for ground operations and ground combat capabilities together with the ongoing transition to a network centric warfare concept can be characterized by the trends listed below. However, substantial research and development efforts, especially in the area of secure and flexible communication between mobile network nodes, can be foreseen to create the necessary technology.

- The development in information technology and communication can potentially provide means for command and control of ground units and systems (manned or unmanned) over great distances and in real time (or close to real time).

- Sensors will be used for reconnaissance and surveillance of large areas.

- Development of multi-static radar systems and techniques such as millimetre radars will increase the capability of collecting data in the conflict area or the battlefield. The development of low-frequency radars can, in spite of camouflage and stealth design of potential targets, increase the probability of detection.

- The development of multi-sensor technologies that provide day-and-night as well as all-weather capabilities increase both possibilities and threats when it comes to surveillance, command and control, and engagement systems.

- Combat in urban environments can be supported by advanced systems e.g. sensors and identification systems, adaptive command and control systems (including e.g. flexibilities with respect to map presentations), and non-lethal weapons.

- New advanced technologies supporting the soldier on the ground, especially in the areas of sensors, communications, and information systems.

2.3. Benefits, limitations and requirements, technical

2.3.1. General

The first step in this study is to define the functions to be performed by the multifunction RF system. Table 1 presents typical functions associated with traditional radar, electronic warfare and communication.

Radar	Electronic warfare	Communication
- Volume surveillance - Detection & confirmation - Target tracking - Target identification - Target trajectory calculation - Tracking of ECM emission - Kill assessment - Missile communication - Counter-countermeasure (ECCM)	- Radar warning receiver (RWR) - Electronic support measure (ESM) - Electronic countermeasure (ECM) - Electronic intelligence (ELINT) - Communication intelligence (COMINT)	- Distribution of information Transfer of best effort services and services of guaranteed quality through point-to-point/multi-point connections or broadcast. - Exampel of external services Command and Control services Position Distribution services Situation awareness services Sensor data/information services

Table 1 Typical functions associated with radar-, electronic warfare- and communication systems.

The requirements imposed on the design of the above functions depend very much on the environment in which the system must operate, on which platform the system is to be deployed, the specifics of the missions to be accomplished and the class of personel that will operate the system. Table 2 highlights some of the parameters that affect the system functions and performance.

	Radar	Electronic warfare	Communication
Operational environment	- Type of weapons - Interference - Jamming - Clutters - Target size & density	- Guided weapons and their range - Type of radars - Radar range - Signal traffic density	- Interference - Jamming - Propagation environment
Deployment	- Land-based - Shipboard - Airborne		
System users	- Cost - Complexity - Redundancy		

Table 2 Parameters that affect system functionality and performance.

It is not the intent of this report to describe or identify specific known radar, EW and communication systems. The functions associated to radar, EW and communications systems are described and discussed in a generic fashion.

2.3.2. Electronic Warfare aspects

In this section, two divisions will be discussed: electronic support and electronic attack (also referred to as electronic countermeasures). There is a substantial number of publications on these topics in the open literature, so only a brief introduction to this area is given. Some important aspects of using an MFA for EW functions will also be discussed.

Electronic Support (ES)

Passive use of the microwave part of the electromagnetic spectrum is a powerful tool in order to protect platforms or support targeting functions. In the defensive ES roll (usually called RWR), high probability of intercept (POI) is the priority design parameter. For this reason, instantaneous spherical coverage is essential as well as instantaneous bandwidth corresponding to all possible threat emitters. Examples of characteristics of commercially available RWR systems are given in table 3. An operational goal is to maintain the coverage 100% of the time. When using a multifunction system, this might not be possible if the apertures are shared with transmitting functions using T/R-modules. Even when separated transmitting and receiving arrays are used, reaching the appropriate isolation is a delicate issue.

Type	Sensitivity (dBm)	Probability of Intercept (POI)
Crystal video	-40/50	Very high
Narrowband superheterodyne	-70/80	Low
Tuned RF	-50	Medium
Wideband superheterodyne	-60	High
Wideband superheterodyne with channelized Rx	-70/80	High

Table 3 Performance of available RWR systems [4]

A conventional RWR use multiple, broad beam antennas and wideband receivers to fulfil the high probability of intercept requirements. The directions of arrival (DOA) to the illuminating emitters are usually measured on monopulse basis by comparing amplitude or phase responses from the antennas of the RWR system. With the described combination of low gain antennas and wideband receivers the resulting system sensitivity is modest. Nevertheless, the platform with a RWR-functionality is the winner in the detection range duel against most radars.

The sensitivity and the detection range can be extended by reducing the noise bandwidth of the receivers. In order to preserve the high POI, a multichannel approach is preferred instead of a frequency scanning design. Channelized receivers are also a better choice in dense signal environments. In order to achieve instantaneous spherical coverage in an MFA-system based on plane arrays, a number of apertures facing different directions have to be used. Each aperture could be configured to produce accurate direction of arrival information in two orthogonal dimensions. These two dimensional DOA measurements support the RWR geolocation capability and ease the necessary deinterleaving process, especially in a dense signal environment. The DOA information is also useful for cueing the ECM or the radar functions. An important design issue is whether the RWR function should be using multibeam capabilities in each array. A multibeam approach would improve system sensitivity, which would affect the detection range and enhance the measuring accuracy of all estimated parameters, including direction of arrival. The spatial separation resulting from a multibeam solution could also be very useful. In the end the selected design is a trade off between performance and complexity.

In the offensive ES roll (usually called ESM) the lower POI resulting from use of narrow beams and search processes can be accepted. The scan-on-scan detection problem is reduced if the ESM function sensitivity is high enough for detection in the radar sidlobes. Multichannel and multibeam capability is preferred but instantaneous spherical coverage is not required. ESM direction of arrival measurements can be used to cue the antenna beam used by the radar functions. The other way around the radar function is capable of cueing the ESM antenna beam in order to classify or identify a target detected. Of course detections made by the RWR function could similarly be transferred to the ESM function with the purpose of better measurement accuracy. In a radar-like manner the ESM function can use the agile MFA beams to perform track-while-scan.

Design goals for a modern high-performance ES system according to Schleher [5] are listed in table 4.

Frequency range	0,5-40 GHz
Signal type	50 ns pulse to CW
Sensitivity	<-70 dBm
Frequency resolution	< 2 MHz
Dynamic range	> 70 dB
Amplitude accuracy	1 dB
Bearing accuracy	<1° rms
Pulsewidth resolution	25 ns
TOA resolution	50 ns
Probability of intercept (POI)	100%
Pulse rate	10^7 pulses/s

Table 4 Examples of modern ES system design goals according to Schleher [5].

Both the RWR and the ESM functions are improved if polarization diversity is included in the MFA capability in order to minimize polarization mismatch losses. Based on a monopulse approach, polarization measurement capacity could significantly increase the pulse inter-leaving robustness, that is when confronted radars without polarization agility.

The communication capabilities of the MFA system are possible to use by the ES function to achieve multi platform advantages, such as rapid geolocation. In a multi platform scenario the MFA communication functions also make it possible to operate some of the platforms in a silent mode. Hence, the ES performance is not degraded by transmitting radar or ECM functions. Combined with low radar cross section a silent operation mode denies the enemy situational awareness.

Electronic Attack (EA)

Two of the most important parameters for a countermeasure system are the operating bandwidth and the Effective Radiated Power (ERP). A multifunction antenna has to combine the demands of both a radar and an electronic warfare system. For a proper function, resource management is of greatest importance to fulfill all the system functions. The tactical situation determines which role the MFA shall be assigned each moment.

In a combat situation it is very important that the receiver in a countermeasure system can detect and identify the threat signals, and then feed the intercepted signal to the jammer system almost immediately. The ability to polarization control is also a very important parameter. Ideally, the countermeasure system should be able to adapt the transmitted polarization to the received instantaneous polarization (for example when the aircraft is maneuvering). To achieve this kind of polarization agility, the multifunction antenna array will have to be equipped with a sufficient number of antenna elements, and also incorporate polarization control circuits.

An electronic countermeasure system has to cooperate with a suitable electronic support measure system to work properly. One parameter which will influence the system behaviour is if the transmit and receive arrays are separated, or if a combined transmit/receive array using T/R-modules is used. In the case where the transmit and receive apertures are separated, the problem with directing the transmitting lobe in the same direction as the receive lobe will have to be addressed. The benefit would in this case be that it might be possible to transmit while receiving (if the interference aspects can be handled). If a combined aperture using T/R-modules is chosen, the jammer system will have to be able to adapt its behaivour to the type of threat to be countered. When jamming a coherent radar, one pulse in a coherent processing interval (CPI) can be stored in the system and repeated the rest of the CPI. In case of a non-coherent radar, the approach would be to store a part of the pulse and repeat it in sequence until a full pulse length is reached.

One obvious benefit of an array antenna is the freedom to control the antenna lobe very quickly between different threats, and also adapt the antenna lobe width to the most suitable size for the moment. Directing the jammer antenna lobe requires measurement of the angle of arrival of the threat signal. A rule of thumb for existing system designs is to use one third of the transmitting antenna lobewidth for the receiving lobewidth.

More than one threat can be handled if the system uses time sharing between the threats. Another way to handle several threats simultaneously is to allow for the system to form multiple lobes, e.g. by dividing the aperture in a number of sub arrays, each of which will be able to counter different threats. One disadvantage with dividing the array is that the lobe width will increase, and that the ERP will be substantially lower.

Generally speaking, two types of jamming can be identified, reactive (responding to an received radar pulse), and proactive (jamming with for example barrage noise in a bandwidth where the threat radar probably will operate).

The jamming function is often characterized in categories, briefly described below.

- Self protection jammer (SPJ) for both aircraft and ships. The system will counter the immediate threat, which can be fire control radars and missile seekers. This type of jammer has moderate need for transmitting power. The use of an array antenna on an airplane is very interesting in this context. It should be possible to cover the whole sphere around an airplane with six arrays, thereby giving the pilot the full freedom of manoeuvring the airplane with maintained system functionality.

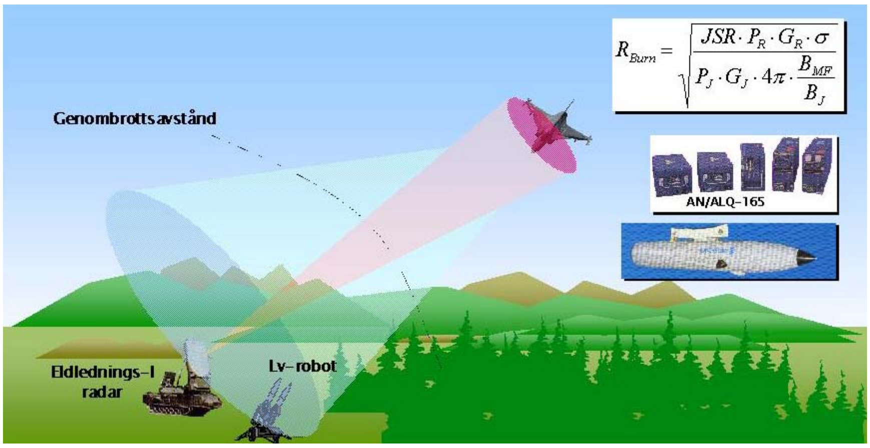

Figure 2 Self protection jammer

- Escort jamming can also counter search radars to mask for example a strike package. This can be achieved by a jammer equipped airplane which follows the strike package all the way to the mission target. The need of ERP is slightly bigger for this type of system than for the self protection jammer.

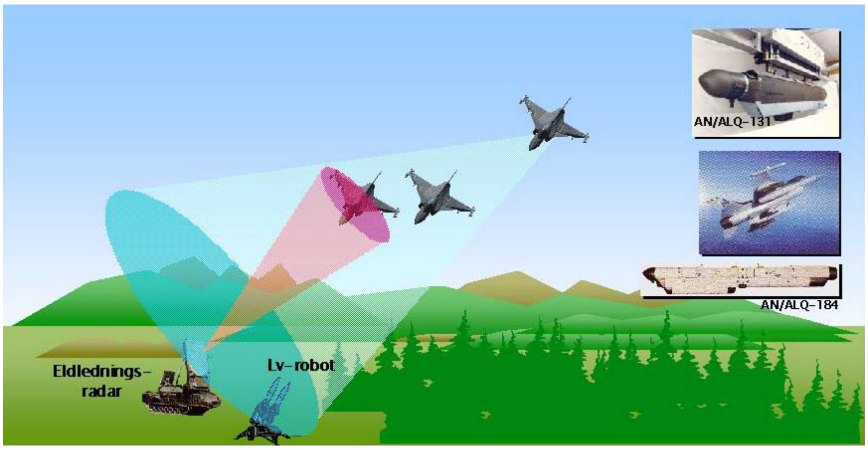

Figure 3 Escort jamming

- Stand off jamming (SOJ) is most commonly used for masking a strike package at greater distances. This jamming function is the most demanding with respect to ERP requirements. The amount of power needed is depending on the RCS of the platforms to be protected, and also on the distance between target, threat and the jammer. This type of jamming is preferably performed in the main lobe of the threat system. For side lobe jamming, the need for power is very big; the jammer has to increase the jamming power proportional to the side lobe suppression. To protect a battleship, the demand for output power will in this case be tremendous.

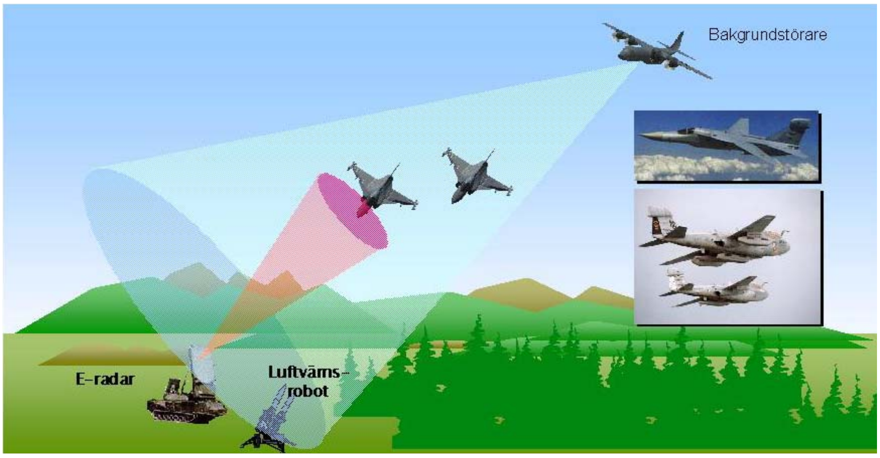

Figure 4 Stand off jamming

For escort jamming and stand off jamming the required ERP to perform successful jamming can be lowered if the jamming platform can be located between the threat and the protected platform. This should be possible to accomplish by using a UAV as a jamming platform.

2.3.3. Radar aspects

Future radar systems will be designed as multifunction radars with array antennas and powerful signal processing and data processing [6]. Several simultaneous functions for target search, track and recognition will be possible. Adaptive and flexible control give optimised performance with increased jamming resistance and robustness. Signal processing and data processing for active digital array antennas combined with advanced waveforms and measurement geometries give new possibilities to suppression of jamming and clutter and increased range and accuracy of the radar system.

Depending on the application the future multifunction radar faces a very diverse set of operational requirements. Among the important considerations are the characteristics of the targets in terms of number at any time, the rate of arrival, their size and spatial distribution. Difficult targets of the future can be combinations of stealth platforms and stealth missiles. Due to their low radar cross section the detection will require improved sensitivity and high power search radar. Tracking of low observable targets must be initiated by a sufficiently accurate search function to cue the tracking function. For the recognition function the multifunction radar alone will probably not be sufficiently effective. Recognition will be accomplished most effectively and robustly together with passive electronic reconnaissance.

Developments in multifunction radar design will give improved radar system concepts for weapon platforms and command and control systems. Increased modularity, flexible control, decreased vulnerability and increased jamming resistance will result in new concepts for command and control systems and weapon platforms with limited space and shared apertures with other command and control and electronic warfare systems. The threat environment and requirements on cost-effectiveness make multifunction radar more important for future army, navy and air force radar applications.

The most important component in multifunction radar is the active digital array antenna and the associated signal processing. An important part of the antenna system is an accurate calibration and compensation of the antenna signals to give low sidelobes and accurate target measurements. The active digital array antenna gives new possibilities for beamforming and control with increased jamming resistance and robustness. Conventional beamforming can generate multiple beams in different directions. Different beamshapes can be optimised to detection and tracking of targets. Adaptive beamforming and processing to suppress clutter and jamming is integrated into the digital beamforming. Model based processing is possible for increased resolution and detection performance. Adaptive and flexible control of the digital beamforming and antenna array processing can be used optimise performance.

The use of an active array antenna provides the ability to control the radar parameters in real time and to adapt to the changing threat environment. Some adaptive features are:

- digital beamforming
- waveform generation
- beam management
- frequency selection
- task scheduling
- tracking

The increase in performance of the active digital array multifunction radar gives highly flexible and versatile operation. It is possible to design a radar that react to changes in the threat scenarios and that adapt parameters to optimise performance.
The multifunction radar is required to perform a number of functions generate and maintain target data and to assist weapon systems to engage targets. Some functions are:

- volume surveillance
- target detection and confirmation
- target tracking
- target identification, co-operative and non co-operative
- target trajectory and impact computation
- tracking ECM emission
- kill assessment
- missile communication

Some design limitations that also must be considered in the future scenario are:

- stealth targets
- rapid reaction and update
- highly manoeuvrable targets
- multiple targets
- very low altitude targets
- intense jamming
- severe clutter
- weight and power limitations
- mobility

The active digital array multifunction radar can provide several new and improved features compared to more classical design. In some cases it is the only possible solution. The improved flexibility must be carefully used and ensured by strict design to benefit from the expected performance and to fulfil the future requirements.

Two major functions that shape the design of a multifunction radar system are the search and track functions. The search and track functions have different characteristics and performance requirements that will influence the design of the multifunction system.

Some generic characteristics and requirements of the search function are:

- several operating modes to adapt search volumes to different targets
- radar energy must be optimised to changing target range and size
- maintaining probability of detection for all targets
- full flexibility of resource allocation, spatial and temporal
- multiple beam capability to shape search volumes
- ECCM to reduce the effectiveness of jamming

Some generic characteristics and requirements of the track function are:

- fast target acquisition and track initiation
- tracking of several targets simultaneously
- maintaining tracking accuracy for all targets
- several tracking modes depending on target range and priority
- ECCM to reduce the effectiveness of jamming

2.3.4. Communication aspects

The communications function is to transfer or distribute information. To do so, communications systems typically support guaranteed quality of services and best effort services. Examples of external services that communications systems are to support are:

- command and control services
- position distribution services
- situation awareness services
- sensor data/information distribution services

The guaranteed quality of services usage is required in time critical external services. Typically, these services require that the maximum and average of the following parameters are described:

- time delay
- time jitter
- transfer speed
- loss ratio

The description of the parameters above can be defined from bit level, via different packet layers, up to the very external service layer.

As mentioned earlier, radar and EW benefit from the use of antenna arrays and beamforming. However, employing multiple antenna elements is also a key technology in optimizing the performance of a military radio communication system and the benefits are concluded in the following points.

Beamforming increases:

- Capacity
- Availability
- Coverage/Range
- Mobility
- Robustness
- Stealth performance
- Network performance

Beamforming decreases:

- Power consumption
- Delay

In this section the benefits of using antenna arrays and beamforming for communications will be approached in two different ways. Depending on the situation (platform, environment, mission etc.) either *bandwidth efficiency* or *power efficiency* is more important.

If the MFA is to be used on a small platform, for example a UAV, where weight and space is limited, power efficiency is of outmost importance. That is, the weight and size of the power generating units that the UAV needs to carry is to be minimized. By using beamforming less power needs to be transmitted to maintain a required capacity, compared to a uniformly radiating antenna, and the power consumption decreases.

If the MFA is to be used on a larger platform the requirement of power efficiency is not as high but instead high bandwidth efficiency may de desired. Beamforming is a bandwidth efficient technique, which enables increased capacity, availability, coverage and mobility without sacrificing the available spectrum. By directing the main beam towards the receiver capacity can be increased, since less redundant channel coding bits and a more spectrum efficient modulation scheme can be employed, when the signal power at the receiver is increased. Alternatively, if the modulation format and channel code is not changed the use of a beamforming antenna will increase the systems availability and coverage/range. Electrical beam steering facilitates mobility.

If the position of the receiver is unknown the smart antenna can be used for diversity (either classical transmit diversity or Space-time coding) to increase capacity and robustness to channel distortions.

An increased signal power at the receiver is directly related to the information bit rate and signal bandwidth. Different services have various requirements on bit error rate to obtain sufficient quality in the transmitted information. For example, to receive intelligible speech, it often suffices with a bit error rate of 10^{-3}. For video transmission the requirement on bit error rate is higher, 10^{-5}, and encrypted data transmission requires a bit error rate of about 10^{-7}. Services with high requirements on a low bit error rate are most often, high bit rate services. Hence, the use of smart antennas enable transmission of higher bit rate services, assuming all other factors are constant. This enables transmission of larger amounts of for example sensor data, which in the long run improves battlefield awareness.

Robustness to jamming, interference and other channel distortions can be increased by employing an adaptive beamforming antenna at the receiver, placing spatial nulls in the direction of jammers and optimizing the antenna gain in the direction of the desired signal.

In military scenarios it is often desirable and sometimes essential to optimize the stealth performance of the communication system, a feature, which can also benefit from using a beamforming antenna for transmission. Allowing the transmitter to direct its main beam towards the receiver will minimize the probability that an adversary intercepts, detects and exploits the transmission.

Network performance can be increased by spatially separating users, Spatial Division Multiple Access (SDMA), enabling them to transmit information on the same frequency at the same time and with the same code (in the case of a Code Division Multiple Access (CDMA) scheme) as long as they are sufficiently separated in space. When using a beamforming antenna it is possible to synthesise multiple beams enabling transmission in several directions at the same time. This is important when considering the platform in a NCW context. The platform should function as a node in a network, being able to maintain communication with a node in a certain direction, and at the same time be able to relay traffic in other directions. Furthermore, in many cases the scenario is dynamic with a high level of mobility among the nodes, which requires electrically steerable antennas to maintain communications with moving nodes. In a NCW context many platforms will be able to share information. This is in many ways made possible by the use of concepts such as an MFA. On the other hand, the sharing of information can also be used to relieve the demands on the MFA. When a platform can obtain data from other platforms, which increases its awareness of the battlefield, it does in some cases not have to use its own radar functions and this will free MFA-resources for communications and EW. In NCW silent mode operation can furthermore more easily be supported, since the platform will obtain situational awareness (SA) data from other platforms. It can act as a passive platform just listening for and receiving data until it changes to an offensive roll such as ESM.

Time division multiple access (TDMA) is a well-known access technique in communications. The user is assigned a time slot during which it is allowed to communicate. This idea could be extended to the multifunction concept by assigning certain time slots to communications and others to EW and radar if it is not possible to perform all functions at the same time. For example, pulsed jamming could be performed occupying some time slots and in between pulses the MFA could use other time slots for communication or radar.

The use of beamforming antennas increases the quality of the radio link as compared to a link with isotropic antennas, assuming equal radiated power. The delay over the link due to repeated retransmissions of erroneous data is thereby decreased and as a consequence the delay in the network is decreased. This is important, since certain services, for example voice transmission, are very sensitive to delay.

2.3.5. Aspects concerning other possible RF functions

In this section, functions related to identification, navigation and position of a platform are discussed. The functions described below are mostly services existing today, and performed by dedicated, off-the-shelf systems. It is judged that the majority of these functions (existing or future) could be performed within the scope of a multifunction system as briefly described in this report.

Global Positioning System (GPS)

For positioning civilian or military GPS-receivers may be used.
Today GPS operates on the two frequencies L1 (1575.42 MHz) and L2 (1227.6 MHz).

Military GPS-receivers can use both L1 and L2, since the encrypted P(Y)-code is employed on both frequencies. This improves positioning accuracy since dual-frequency ionospheric corrections can be applied at the receiver. Furhermore, due to the use of the encrypted P(Y)-code, military receivers are very robust to spoofing[1].

Civilian receivers, which today only use the C/A-code on the L1 frequency, are not as precise as military receivers and they are also more sensitive to jamming. For more information, see [7].

Due to the weak signals GPS-receivers are very sensitive to jamming. There are different ways of protecting the GPS-receiver from being jammed. One way is to use an adaptive antenna to form nulls in the direction of jammers and form beams towards the satellites to be tracked. At least four satellites need to be tracked to be able to estimate both time and the position of the receiver in three dimensions. However, if it is possible to track more than four satellites at the same time the navigation and positioning performance increases. To be able to simultaneously receive signals from multiple satellites, multitarget beamforming has to be performed, i.e. for each satellite a beam has to be formed towards the satellite, at the same time as interfering signals (signals from other GPS-satellites, multipath and jammers) in all other directions are suppressed [8]. Hence, a separate beamformer is needed, for each satellite to be tracked. Digital beamforming antennas reduce the jammer-to-signal ratio and multipath-to-signal ratio, which have a big impact on both the code and carrier phase measurements. This results in an increased accuracy and a shorter Time To First Fix (TTFF)[2] [8].

If the GPS-receiver, despite of the protection of the beamforming antenna, is jammed such that the lock of the satellites is lost, it must start searching for the best constellation of satellites to use. During the time the receiver is jammed and during the TTFF (about 30 seconds in “warm start”), the platform must still be able to navigate. Today, a hot topic for research is the integration of Inertial Navigation and GPS for improved robustness to jamming [7], [9].

GPS is currently being modernized. A new civil signal, L2C, will be added in the L2 band. The civil service will because of this have the possibility to use dual-frequency ionospheric corrections and its accuracy will be increased. However, these signals are not intended for precise navigation. A new military M-code will be added, on both L1 and L2. The implementation of L2C and the M-code on L1 and L2 will start in 2003.

In 2005 a third high power civil signal is to be added at L5 (1176.45 MHz) and used for precise navigation. The robustness of GPS to unintentional interference will be increased, since it is unlikely that it will affect all civilian signals at the same time. The implementation of the L5 signal is expected to start in 2005.

A European equivalent to GPS, called Galileo, is currently being developed. The development phase started in May 2002. It is expected that GPS and Galileo are going to be compatible and interoperable and that this will increase the availability and accuracy of navigation.

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[1] Spoofing = the intentional transmission of a false, but stronger, version of the GPS signal such that it captures the receiver tracking loops and fools the navigation process.
[2] TTFF is defined as the time it takes to find and lock on to the satellites from the time the receiver is turned on.

Radar Altimeter

A radar altimeter uses radar principles for height measurement of a flying vehicle. Radar altimeters are often divided into two types; frequency modulated continious wave (FMCW) and pulse altimeters, depending on the waveforms used. A further classification into broad or narrow beamwidth and short pulse or pulse compression types can also be made. Two frequency bands, centered approximately at 1.6 and 4.3 GHz, have been assigned to radar altimetry.

Typical output power values for commercial altimeter systems ranges from 100 mW to a few watts. The antenna used has a beamwidth of typically tens of degrees (broad beamwidth) down to a few degrees (narrow beamwidth). The use of an active array antenna would probably also create advantages in terms of lowering the probability of enemy intercept of the altimeter signal.

Identification Friend or Foe (IFF)

Modern airborne IFF is a two-channel system, with one frequency (1030 MHz) used for the interrogating signals and another (1090 MHz) for the reply. The system is further broken down into four modes of operation, two for both military and civilian aircraft and two strictly for military use.

Altitude information is provided to the transponder by the air data computer. When interrogated in a predefined mode, the transponder automatically replies with the aircraft altitude. The code signal sent by the interrogator system consists of two pulses spaced at a precisely defined interval. The transponder replies are also in the form of a pulse, though in this case, there are 12 information pulses. There is also a secure mode for military purposes, using an encrypted interrogation signal.

If the IFF function is to be integrated in a multifunction system concept, the possibility to better spatial control over both the reply and the interrogation signals could prove useful.

3. Example of a multifunction system concept

3.1. Overview

Based on knowledge of existing systems and on the discussions above, tables 5 and 6 show roughly the general characteristics of today's receivers and transmitters. As can be seen, the RF requirements for different applications can differ significantly which impose some sort of RF compromises when using a single RF front-end to support the system functions.

Characteristics	Radar	EW	Communication
Applications	Search, tracking, weather …	RWR, ESM, ELINT, COMINT	Point-to-point, point-to-multi-points
Frequency range	1-100 GHz	1-100 GHz	0.001-60 GHz
System bandwidth	Several MHz – 3 GHz	Several GHz	Several MHz
Sensitivity	High	High	Moderate
Dynamic range	High	High	Moderate

Table 5 General characteristics of today's receivers

Characteristics	Radar	EW (ECM)	Communication
Type	1) Ground based and shipborne 2) Airborne	1) Ground based and shipborne 2) Airborne	Point-to-point, point-to-multi-points
Frequency range	1-100 GHz	1-100 GHz	0.001-60 GHz
Power range (kW)	1) 1-5000 2) 0.5-1000	1) 0.2-10 2) 0.2-2	0.01-1

Table 6 General characteristics of today's transmitters

Below, the different steps that are recommended in order to establish the basic requirements for a single RF front-end system are summarized.

a) Define the system functions that should be performed by the system.

b) Address all aspect of performance (specifications), including specifications and limitations imposed by the platform. This will be a joint effort between the system user and the designers.

c) Define the functions with higher priority in the first position.

d) Segment the problem in two main blocks: T/R module and feed/beamformer network.

e) The T/R module: (technology related)
   - Receiver: signal/system bandwidth, sensitivity, dynamic range, IMD products, filtering etc.
   - Transmitter: power level, bandwidth/power efficiency, input power/power efficiency etc.
   - Isolation between the receiver and transmitter

f) The feed/beamformer network: (architecture related)
  - Radar functions require DBF while EW functions and comm. can be performed using ABF: so how can we integrate DBF and ABF using the same network?
  - Different functions require different beamshape: flexible and reconfigurable beamformer is necessary.

When making the analysis according to the steps indicated above it can be concluded that one of the most striking characteristics of a single RF system is the need for many compromises. Once the system functions have been defined, it is possible to determine a system architecture. The system architecture will be shaped depending whether there is a demand to perform several missions simultaneously or one at a time. The system architecture should also be designed for graceful degradation, i.e. in the presence of heavy traffic and interference the system should not fail completely. It must also be stressed that successful system architecture design depends mainly on a good knowledge of modern techniques and technologies.

Following is an example of a broadband single RF system concept for multifunction array system, shown in figure 5 and 6. Key blocks such as FC1 and FC2 (active reconfigurable power splitters/combiners), MFAM (multifunction active matrice) and T/R module will have to be further studied and evaluated based on the established requirements for a single RF system. This is not within the scope of the work reported here. However, a brief description of the proposed concept will follow below.

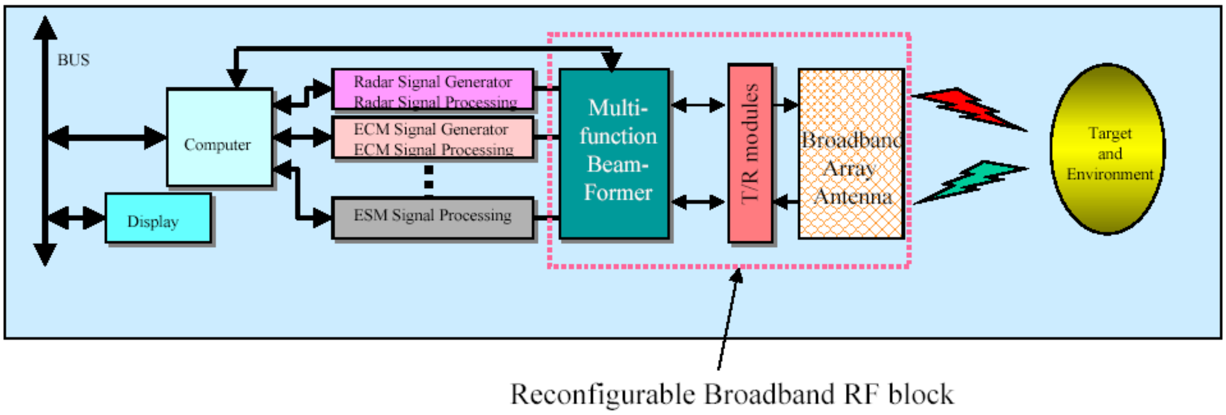

Figure 5 Schematic diagram for a multifunction active phased array system

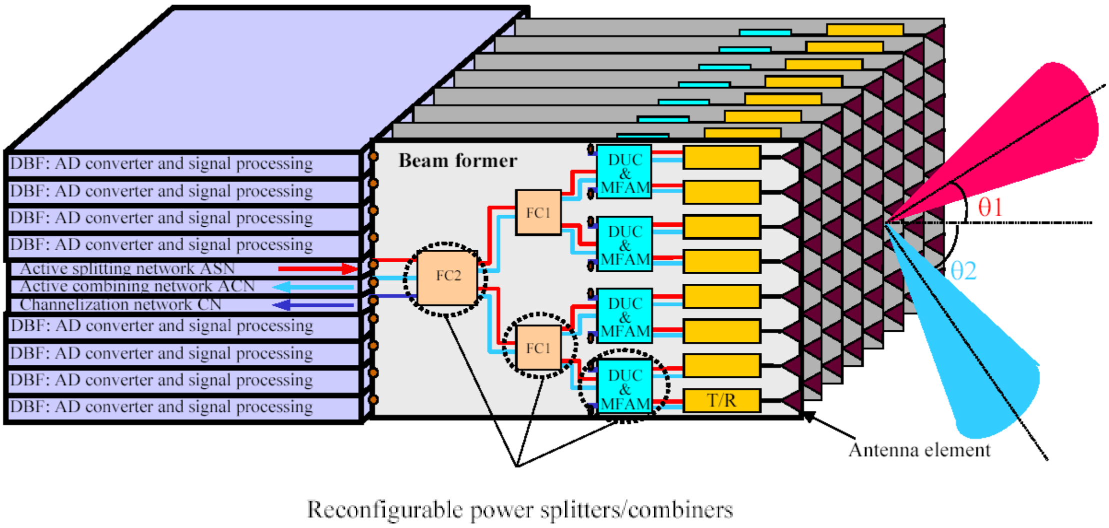

Figure 6 *Chameleon Concept: Broadband single RF system for multifunction array antenna*

3.2. Transmit and receive modules

Figure 7 shows a block diagram of a highly integrated TR module. It is composed of a multi-polarization block to acheive the polarization required for the various system functions (polarization diversity), a variable gain driving dual medium amplifier (DMPA), a reconfigurable dual high power amplifier (DHPA) to satisfy the power requirement of the various system functions and a dual low noise amplifier (DLNA) for the receiver channel. The single pole-double throw switches (SP2T) are used to switch between the transmission and reception modes. These are in turn connected to the antenna elements TSA. The limiters are used to protect the receiving channels from high power signals, can be either from friendly or enemy systems. Depending on the RF isolation requirement, different integration solutions can be implemented. If a high isolation is required between the transmitter and receiver channels, the transmitter antenna and receiver antenna are to be separated. As a consequence, the power amplifier will be located as close as possible to the transmitter antenna and the low noise amplifier as close as possible to the receiver antenna. On the other hand, the multi-polarization chip can be shared between transmitting and receiving channels.
The different colours in the diagram reflect the need of using different semiconductor technologies depending on the power and noise requirements.

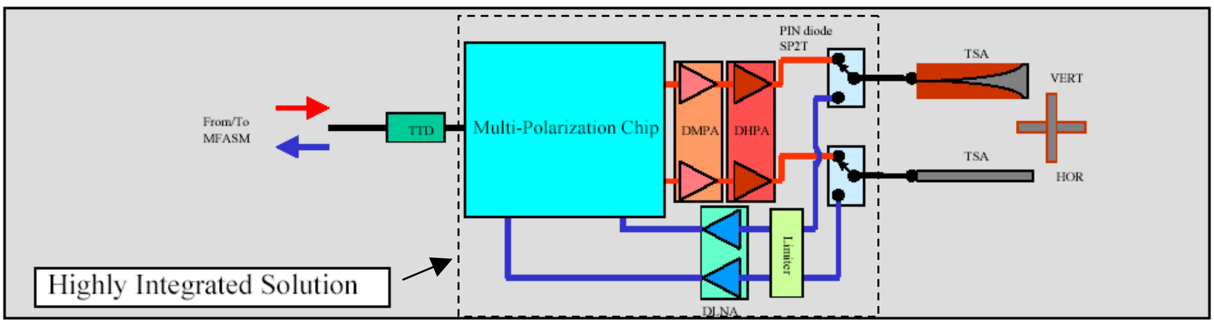

Figure 7 *Block diagram of a highly integrated broadband TR module*

3.3. Beamforming network

Since radar functions require digital beamforming techniques while EW functions and communication can be performed using analogue beamforming, a beamformer that allows both techniques is desirable. Different system functions require different beamshape, thus a flexible and a reconfigurable beamformer is also desirable. Figure 6 shows a possible realization of such beamformer. The key blocks in this beamformer are the reconfigurable power splitters/combiners (FC1and FC2) and the multifunction active matrix (MFAM), which include the up/down converters for the digital beamforming network. The wide bandwidth of the system requires the use of true time delays in order to eliminate the beam squint and pulse stretching effects occurred when using phase shifters. Using the 3D-MMIC technique a high circuit integration can be achieved which results in a very compact beamformer.

3.4. Aspect of signal processing and signal generation

3.4.1. Radar

Signal processing for radar applications consists mainly of processing in angle, range and doppler to integrate target signals and to suppress noise, clutter and jamming signals. The signal processing transforms the input signals by beamforming, matched filtering and doppler filtering before detection of targets and estimation of target parameters. The input signal domain is a multidimensional data set consisting of antenna channels, time delay samples and repeated pulses. This data set is also known as the radar data cube. During the coherent processing interval the data cube is processed to give an output data set with dimensions in angle, range and doppler. Targets in the output data set are detected by a threshold function to give target detections. Target parameter estimation uses samples of the output data set around each target to measure the target angle, range and doppler. The detected and estimated targets are then processed in the data processing to track targets and perform other functions.

In many cases the coherently integrated data is further integrated by non-coherent integration that operate on target detections or some other non-linear function of the output data set. This is especially useful for fluctuating targets and can also be combined with ambiguity resolution in many radar modes. Non-coherent integration is also important in imaging radar to reduce speckle and improve radiometric accuracy.

Non-linear processing is also inherent in adaptive signal processing to suppress clutter and jamming and model based signal processing to extract target parameters and perform high-resolution measurements. Many radar signal processing algorithms use the received input data to adapt and control processing parameters. An important signal processing characteristic is the control of false alarms and other errors from noise, clutter and jamming.

Signal generation for radar applications usually involve coherent pulse trains that define the coherent processing interval of the radar. Each pulse can be a complex waveform that is repeated for each pulse or changing from pulse to pulse. The main characteristic is that the waveform is known so that matched filtering and other coherent processing can be done in the signal processing. Modern signal generation techniques allow complex amplitude and phase modulation over wide bandwidths and long time intervals to give large time-bandwidth product waveforms. Very precise and accurate waveforms can be generated with low phase noise that allows sensitive radar functions in large clutter backgrounds.

3.4.2. EW

For jammer applications there are different types of modulations and signal types. The instantaneous bandwidth of the signals can vary from a few MHz up to the GHz-region, typical for SAR-applications.

Noise jamming can e.g. be performed with different bandwidths depending on the type of radar to be jammed. A frequency agile radar which change frequency on a pulse by pulse basis requires the use of broadband barrage noise covering the operating bandwidth of the radar. A pulse doppler radar, on the other hand, is integrating a number of pulses under an Coherent Processing Interval (CPI). During the integration interval the radar keeps the frequency, PRF and pulse length constant. The radar has a number of doppler bins

$$N_{doppler} = \frac{t_{CPI}}{PRI} \qquad (1)$$

where t_{CPI} is the integration time. In this case it is possible to mask a few doppler bins with doppler noise, thereby masking the velocity of the aircraft only. If a number of radar systems shall be jammed, the noise bandwidth must cover the operating bandwidth of all radars involved.

It is also preferable for the system to be able to perform pulse modulated jamming. By equipping the jammer with a DRFM (Digital RF Memory), a stored replica of the radar signal can be repeated as many times as desired. When jamming in a so-called multiple false targets (MFT) mode, the stored signal is repeated continuously which will give the transmitted signal the nature of an interrupted CW.
If deception jamming is to be performed, the system must be able to transmit signals indicating a false range detection. In this mode the signal is delayed with an increasing delay time. False velocities can be created by applying frequency offsets on the signal.

3.4.3. Communications

In radio communications, techniques such as channel coding, modulation and spread spectrum are frequently used. Common to most systems are that capacity is to be optimized. However, a military communication system also puts requirements on the ability to communicate without the enemy noticing it (i.e. stealth communications) and robustness to jamming. Below the most common techniques are briefly described. For a more thorough description the reader is referred to [10], [11] and [12].

Channel codes are applied to reduce the errors that the fluctuating radio channel induces on the transmitted data. Often an interleaver is used in combination with a channel code to spread out errors, which would otherwise occur in bursts, since most channel codes are optimized for uniformly distributed bit errors. There is a trade-off between the error correcting capability of the code and the bandwidth efficiency. The more redundant code symbols that are applied the stronger the error correcting capability but the lower the bandwidth efficiency i.e. a larger portion of the capacity of the radio link is used to transmit redundant code symbols. In a military communication system, which has to be robust not only to interferences, but also to jamming, a strong error correcting code may have to be used.

The modulation formats Phase shift keying (PSK) and frequency shift keying (FSK) are frequently used due to their insensitivity to amplitude fluctuations. The best modulation to use is dependent on the environment. PSK is more bandwidth efficient than FSK but the latter is more power efficient than the former. When considering modulation, there is a trade-off between capacity and error probability. The higher the modulation scheme the higher the capacity, but the higher is also the error probability (assuming equal radiated power).

Spread-Spectrum (SS) techniques can be divided into two categories, Frequency-Hopping (FH) and Direct Sequence (DS) spread spectrum, which are both used in military communication systems. Both techniques can be used to control access to the shared resources in a multi-user system (i.e. the radio channel).

FH is an efficient technique to avoid the effects of jamming. Assuming the system alters frequency fast enough the effect of any type of jammer is only an increase in the noise level.

DS is a common technique used for stealth communications. The signal is multiplied with a chip sequence of much higher frequency causing the signal to be spread over a large bandwidth. As a consequence the power density is reduced causing the desired signal to lie below the noise-floor. This makes the signal very hard to detect. In the receiver the received signal is multiplied with the same chip sequence as in the transmitter causing the signal to emerge from the noise floor. Receivers, such as enemy ones, which do not posses the correct chip sequence, will have difficulties obtaining the “hidden” signal.

The type of modulation and code to use depends on the environment in which the link is to operate as well as the required services.

A fixed radio solution can be made very robust to for example jamming by using a strong code and a low order modulation scheme and combine it with frequency hopping or direct sequence spread spectrum. However, such a solution would not be very good from a capacity point of view. To optimize the performance of a communication link one wants to use a code with as few redundant code symbols as possible and as high order modulation scheme as possible given requirements on the error probability. Since military operations often require a high level of mobility and the radio channel is fluctuating, a flexible radio solution, which can change its techniques depending on the environment, like a chameleon, would be desirable.

With the substantial technological progress in architecture design and digital signal processing hardware i.e. ADC (analog-to-digital converters), DAC (digital-to-analog converters), FPGA (Field Programmable Gate Arrays), ASICs (Application Specific Integrated Circuits) and DSP (digital signal processors), an increasing number of radio functions will be implemented in software, i.e. software defined radio [13]. This will facilitate the realization of a very flexible radio solution, in which adaptation between different techniques is possible. That is, coding, modulation, hopping rate etc. can be changed “instantaneously” to adapt to the signal environment and hence optimize the performance of the radio.

3.5. Resource management

Resource management for a multifunction system involves the array antenna apertures, time scheduling, beam management, waveform control, energy and power management and signal and data processing management. The resources can be shared simultaneously or shared in a time sequence. Some resource sharing might not be possible such as transmitting and receiving at the same time and frequency in a T/R module. Other resource sharing might not be possible due to limitations in transmit power output, data rates, processing rates and signal channel allocation. Some functions require resources in response to external signals and actions and in these cases the multifunction system has to queue and execute the functions in some priority order. This part of the resource management is a complex multidimensional scheduling problem that has to be solved.

The resource management for a multifunction system is a part of the command and control structure for the platforms and network that carry the multifunction system. The control system is an event based decision support system that can handle events with uncertainties. The control system can be structured in a hierarchy with different levels of process control. The process levels for a multifunction system can be hardware control, functions, missions and command. In each level there are agents (programs or operators) that can start processes and interact with other levels. Each process has start and stop conditions and gives results to the agents on different levels. The decision loops in the resource management consist of planning, scheduling, administration, fusion and conflict management.

A model for the resource management is based on a dynamic market with sellers, buyers and brokers. In this case the multifunction system can be used by external operators on a dynamic basis and not only be an exclusive resource for the multifunction system platform. This model is also used for the different levels in the above control system.

4. Design principles for a system simulator

There are many different ways in which a multifunction antenna can bee seen. This is partly because different persons mean different things by a multifunction antenna, but it is probably mostly because people with different backgrounds put focus on different things. We believe that it is good to try to study a problem from several different aspects. In section 2.1, we have seen one view of a multifunction antenna. Here is another view.
The multifunction system can be described by the objects in figure 8. There are also data paths between the object "Resource Allocation" and the object "Signal processing". Also there are data paths from the antenna through the "Air" to the "Target Objects" and back to the antenna.

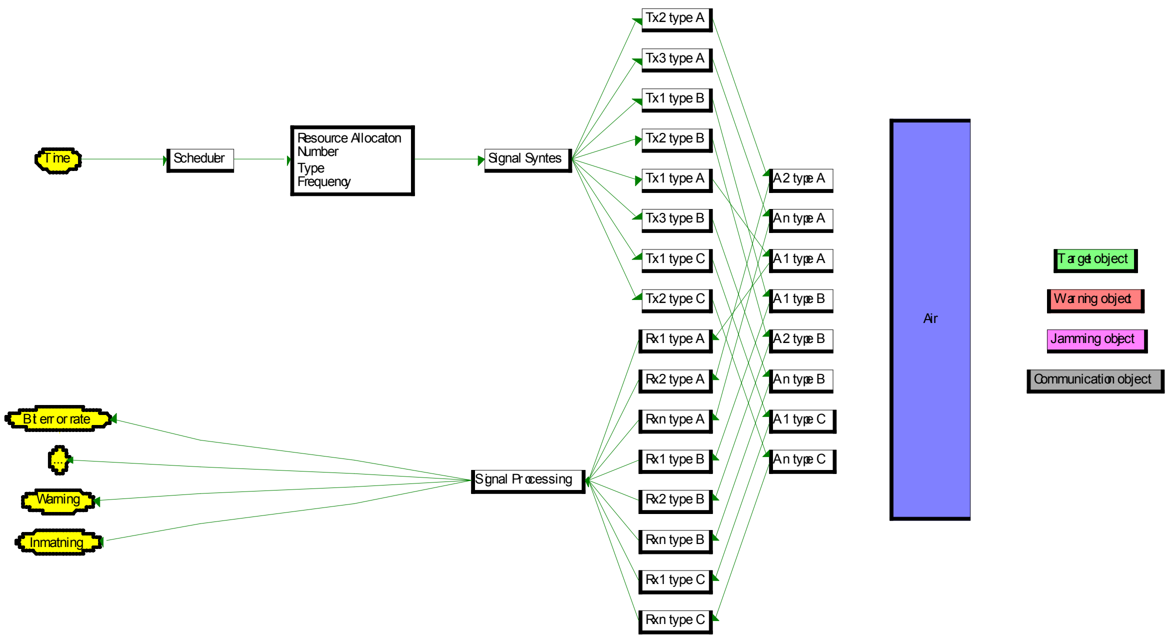

Figure 8 One possible view of the multifunction antenna

4.1. Objectives for simulation

In this section we give a list of different objectives for simulation. We try to state what models that are needed for each objective. We also try to set a priority for each task.

The objective for a simulation is to investigate the performance of the multifunction antenna in a certain scenario. A single simulation should be able to answer what would happen in a specific scenario with a specific set of parameters. This type of simulation will generally require a rather high fidelity in the models if accurate results are to be obtained.

It is often more interesting to acquire a statistical measure. For instance, it may be more interesting to display the POI, rather than the state ‘intercept’ or ‘no intercept’. Such measures can in principle be obtained in two ways. They can either be computed as mean values of a large number of deterministic simulations with randomised parameters, or they can be obtained by analysing the statistics of the processes that are involved.

Objective	Prio	Needed models	Fidelity	Note
Bit error rate, Data rate Continuity in communication	1	Communication Transmitter Receiver Antenna Propagation	Medium Low Low Low Medium	Simple models require only SNR and assumptions about modulation scheme.
Detection probability False alarm rate, Measurement accuracy	2	Radar Transmitter Receiver Antenna Propagation Radar cross section	Medium Low Medium Medium Medium Low	
Target recognition	3	Radar Transmitter Receiver Antenna Propagation Radar cross section	High Medium High Medium Medium High	
POI DOA accuracy	2	RWR / ESM Receiver Antenna Propagation Threat system	Medium Medium Medium Medium Medium	
ERP Power at target site	1	ECM Transmitter Antenna Propagation	Medium Low Low Low	No receiver is necessary. Requires high power model of the transmitter.
Individual receiver/transmitter channels	3	Transmitter Receiver Antenna Propagation	High High High Medium	
Intersystem interference, Instantaneous frequency division versus time division	3	Transmitter Receiver Antenna Isolation	High High High High	Requires description of near field interactions within antennas and between antennas close to each other
Different system configurations	3			Requires possibility to display pre computed results in parallel with the current computation.

Table 7 Simulation objective table

A statistical model can be of lower fidelity than a deterministic one, but it can be very difficult to extract the parameters that are needed to make a statistic model, so it is not necessarily easier to build a low fidelity model than a high fidelity model.

In table 7 we have listed a number of objectives for simulation and tried to give them a priority order. We have also tried to state what level of fidelity that is needed for a meaningful simulation. What is meant by low medium and high fidelity is a bit fuzzy. In a low level

fidelity model there cannot be made any demands on accurate timing and phase information, while such demands may be required from a high fidelity model.
The term priority should mainly be understood as a queue number for in which order the various models should be developed.

4.2. Simulation and model structure

The objective of the simulation is to simulate a multifunction system and to make assessments according to the objectives in chapter 4.1. The simulation system is intended to handle high fidelity electromagnetic models and be able to assess the simulation objectives in a technical/tactical scenario. From a general point of view, when assessing systems using higher level simulations (technical/tactical scenarios) usually simplified models and results from lower level simulations are used, see figure 9.

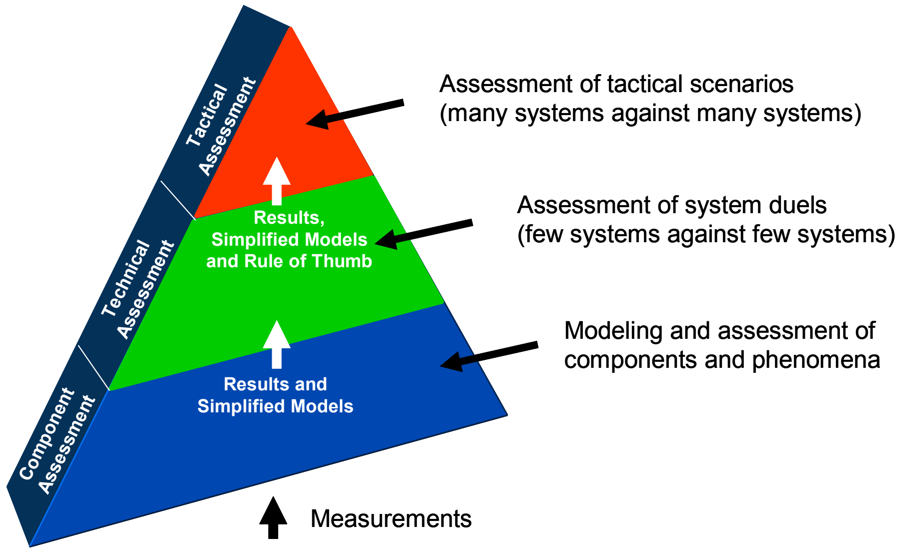

Figure 9 The simulation pyramid.

Too handle these levels (the blue and the green level in figure 9) in one environment is a challenge. To be able to do this, some considerations have to be made which are discussed in the following chapters.

4.2.1. General model structure

An objective of the MFA simulation system is to assess properties of different hardware realisation structures. A model architecture that allows the user to model these structures is of great importance. However, for simulation efficiency it is often necessarily to build a model that does not completely imitate the real hardware structure but emulates the hardware functions properly. Depending upon the use of the model it is necessary to find the sub-models that should emulate real hardware and those that can be simplified to handle hardware functions.

To build a system of different models, two approaches are usually discussed: framework or distributed models. A framework is an environment consisting of quite tightly connected models. Examples of framework environments are FLAMES[3] and STAGE[4]. It is also possible

[3] For more information see http://www.ternion.com/product.htm
[4] For more information see http://www.engenuitytech.com/products/stage/index.html

to develop an in-house framework, an example is OPTSIM [14] developed at FOI. The models in architectures for distributed simulations are more freely interconnected but sharing knowledge of interfaces between the models. Examples of architectures for distributed simulations are: CORBA[5] and HLA[6].

A suggestion for the MFA simulation system is to investigate if any commercial framework can be used or if an in-house framework should be developed. When using a commercial framework, models and tools as scenario editors, terrain database handling, event handling and scheduling functions, data logging, and so forth are usually provided in the product. The framework has of course limitations but provides tools and an infrastructure that relieves the development and makes it possible to concentrate on the important computational models.

If an in-house framework is to be developed, models within the framework should if possible be able to execute in parallel for simulation efficiency. The workload of each parallel model should also be in the same magnitude so that a heavy computing model does not slow down the overall model. If this is not possible a technique to ease the burden of the simulation is to use different time-steps for different models and to predict intermediate results from the time consuming models, see figure 10.

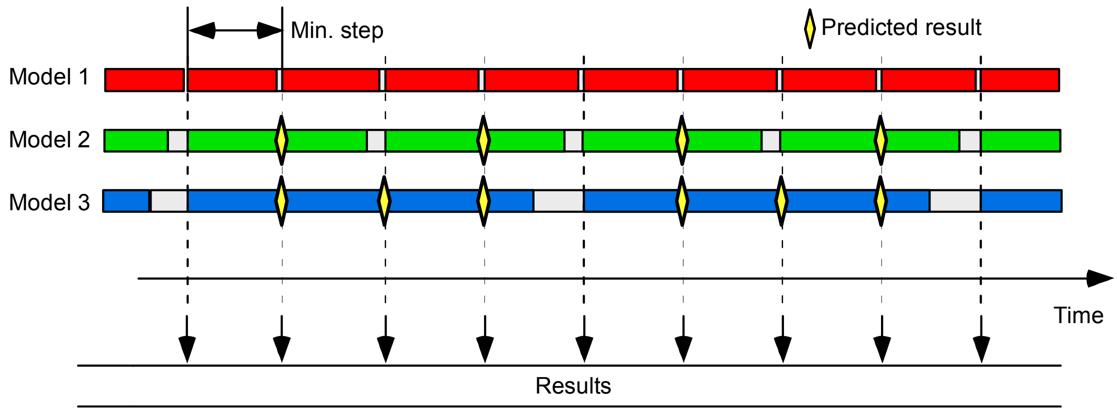

Figure 10 Three parallel models. The red model is always distributing simulated results (a fast or important model in the simulation). The green model distributes simulation results every other time-step, but distributes predicted values in between (a quite important model but with a heavy workload). The blue model distributes values every fourth time-step but distributes predicted values in between (a less important model or a model with heavy workload).

Using this approach, approximations will often be delivered based upon simulations and predictions. The results should be delivered with a quality factor describing the simulation fidelity. Simulation fidelity is also discussed in chapter 4.2.2.

Models that generate static results should execute before the simulation time starts running. A proposed structure is presented in chapter 4.2.3.

The simulation will initially not use any simulation integration algorithms (algorithms that integrate over a time-step to find the states of variable derivatives). Examples of such algorithms are Euler and Runge-Kutta, which are used extensively in simulation languages as ACSL[7] and MATLAB/Simulink[8] to solve differential equations.

[5] For more information see http://www.omg.org/gettingstarted/corbafaq.htm
[6] For more information see https://www.dmso.mil/public/transition/hla/
[7] For more information see http://www.acslsim.com
[8] For more information see http://www.mathworks.com

As the MFA simulations are intended to cover the aspects from component assessment to technical/tactical assessment and the user therefore will be forced to handle a lot of parameters, one essential part of the simulation system will be the user interface. A user-friendly interface is crucial in order to prevent the user from setting wrong parameters and jump to conclusions after a simulation based upon those erroneous parameter values. A clean and instructive user interface without misleading information is important to prevent the user from making such errors. A hierarchical user interface is preferred (hiding seldom accessed parameters or grouping parameters handling special functions) but with the options to easily see parameter values from the underlying interfaces, i.e. a status report review.

4.2.2. Fidelity of simulation

When simulating a tactical/technical scenario it is not feasible to describe the whole scenario using the highest fidelity due to lack of comparable models (a high fidelity electromagnetic antenna calculation will not be comparable to shortcomings in a simplified description of a target radar cross section). Extreme fidelity levels will also make the simulation difficult to set up and slow during execution, finally leading to a never used simulation system. It is therefore crucial to find necessary fidelity levels of each model for each simulation objective described in chapter 4.1.

A model in the MFA simulation system should be able to handle different fidelity levels. In the evolution of a model, intermediate models could function as lower level fidelity models and be integrated in the model code. From the user interface it should be possible to set the fidelity level of each model in the system. A setup routine, that defines suitable model fidelity levels based upon simulation objectives, described in chapter 4.1, would assist the user.

4.2.3. Simulation time aspects

The simulation can be divided into the following sections:

- INITIAL.
  Pre-processing before the simulation time starts running.
  Models that generate static results that are to be used in the simulation and model code that is executed once (variable initialization, etc), should be placed in this section.

- DYNAMIC.
  The simulation is running.
  Models execute and delivers results to the user interface, see figure 10.

- DISCRETE.
  The user interacts with the system (new parameters have been set and a apply button has been pushed) or a mode change in the simulation has been scheduled (i.e. the system switch from being used as a radar warning receiver to handle radar countermeasure) forcing the simulation to handle the new situation.
  In the case of a scheduled event the simulation stops and parameters in the DYNAMIC section are redefined. In the case of user interaction it should be sufficient to stop at the current simulation time. The simulation should not be changed in the DISCRETE section forcing the simulation to start over from the INITAL section.

- TERMINAL.
  Post-processing after the simulation time has stopped or the simulation has been aborted.
  Analysis functions execute to assess the collected data.

Figure 11 shows an example of a program structure and a simulation loop.

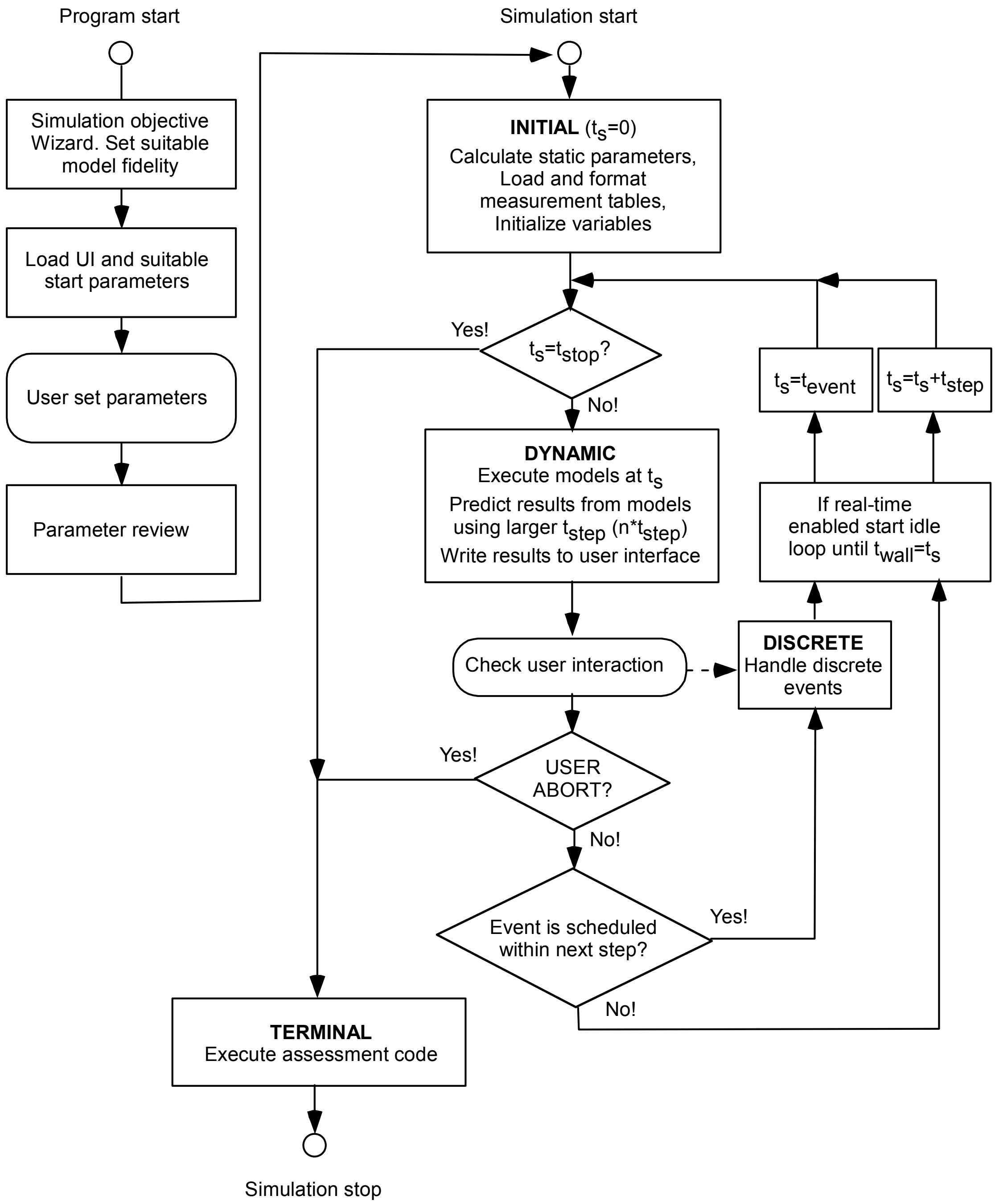

Figure 11 A simulation structure with the program start section included.

4.2.4. How to schedule the scenario

The scheduling of events has the purpose of changing parameters in the simulation objects during the simulation. Two types of scheduled events can be defined:

1. Events pre-programmed to execute at specific times during the simulation.
   A threat radar start tracking the aircraft
2. Events scheduled dynamically during the simulation.
   The radar warning receiver (RWR) detects a hostile tracking radar and schedules the radar countermeasure to counter the threat.

The *first type* of events is defined in the user interface (defining time of schedule and what to occur) before the INITIAL section starts.

```
ts    Event
2.5   RadarThreat1=enable, tracking
10.0  RadarThreat1=disable
...   ...
```

During the INITIAL section an event cue is generated. During the simulation time advance a check is made to see if an event is scheduled within the next time-frame.

The *second type* of event is scheduled depending upon the simulated object states and often generated as a result from an event of the first type. The scheduling could be defined using a script language as the example below.

```
IF RWR_detect(RadarThreat) THEN
      Schedule_Event(ts+0.2, MFA_mode=ECM, ECM_mode=Noise,...)
      Schedule_Event(ts+0.25, ECM=enable)
ELSE IF ... THEN
      ...
ELSE IF ... THEN
      ...
END
```

The RWR detect a hostile radar and an event is scheduled to switch from RWR mode to radar electronic countermeasure mode using noise jamming after a time delay. Another event to enable the countermeasure is also scheduled. The scheduled events are inserted into the event cue. The event cue (above) after the events have been scheduled would be:

```
ts    Event
2.5   RadarThreat1=enable, tracking
2.7   MFA_mode=ECM, ECM_mode=Noise,...
2.75  ECM=enable
10.0  RadarThreat1=disable
...   ...
```

When an event is scheduled to occur within the next time-step the DISCRETE section redefines the simulation objects to handle the new situation and a step to the event time is executed, whereupon the DYNAMIC section simulates the new situation at the scheduled event time, see figure 11.

4.2.5. How to handle user interactions

The user should be able to set parameters in the user interface during the simulation. When the user push the apply button in the user interface the simulation should be able to handle these new parameters. After the DYNAMIC section (see figure 11) a test is made to see if any user interactions have occurred (keyboard polled). If a user interaction have been made the DISCRETE section checks for new parameters and redefines the models for use in the DYNAMIC section.

To be able to handle user interaction the simulation may have to be time regulated. If the simulation is faster then real-time or jerky, the user will have problems to change parameters at desired points during the simulation. To handle this problem an idle loop can be enabled. The idle loop waits (in a while loop) for the wall clock (possibly scaled) to reach the current simulation time t_s.

```
int idleCounter = 0;
while Ts > Tmul * SecondsSinceStartOfSimulation()
{
      idleCounter = idleCounter + 1;
}
```

In the above example code the simulation will loop in the while loop until the function SecondsSinceStartOfSimulation() multiplied by the Tmul factor (Tmul>1 slowing down simulation, Tmul=1 for real-time, Tmul<1 faster then realtime) report a larger value than the simulation time. The idleCounter variable is used to monitor how much idle time the while loop handles and if the idleCounter >> 0 then the simulation could be said to be time regulated.

4.2.6. How to handle time consuming events

Events that require heavy computing and consumes (wall clock) time in the DISCRETE section may have to execute. During such executions time regulations described in chapter 4.2.5 will not work and the user should be informed of what is happening during lengthy operations.

Heavy computing code or part of such code that outputs static results should be placed in the INITIAL section. Heavy computational code that must be executed periodically could be placed in the DISCRETE section and executed by scheduled events. If the code has to be executed dynamically in the DYNAMIC section efforts to split the code in parallel executing models should be made. Setting a longer time-step and predict intermediate results could also be a solution, see chapter 4.2.1.

4.2.7. How to incorporate measurement results

It should be possible to incorporate measurement results and simulation results from more thorough computations. This is similar to computing the results in the INITIAL section, but instead of doing a computation a file is read. The file format needs to be standardised. It should at least be able to read one standard form of S-parameters and one standard form of gain. Examples of such file formats are ‘Touchstone’ and ‘CITIfile’

4.2.8. How to keep track of signal spectrum

We propose that the frequency domain should be partitioned into non overlapping bands and that the signal power in each band should be represented by a uniform power density within each band. Alternatively the power density could have a linear slope in each band. Narrow band signals would then fit in a single band, while broadband signals might be distributed over several bands.

Naturally, it would be nice to handle signals by a complete fourier transform including the phase information, but in order to make use of it, one would probably also need to compute the inverse transformation and compare the signals in time domain. We believe that such a task is too demanding for a simulator of this type. Still, it should be possible to assign phase values to the power densities.

As a first approximation every interaction will be instantaneous, even radar scattering. But if such approximations are made, then it is not possible to analyse radar measurement accuracy for instance.

The next step is to assign time delays for every signal path. A propagation model with multiple paths will then result in signal splitting. If the medium is dispersive then the time delay is not only related to the path length, but also to the signal spectrum. It may be necessary to assign time delays for every frequency band.

4.3. Analysis of simulation objects

4.3.1. Function oriented view

In this section we will give a description of the simulator in terms of functions that must be handled. At a coarse level this is similar to the chart given in section 4.2.3.

- Read configuration files and measured or pre-computed results.
- Write output files.
- Initialise objects, antennas, scenario.
- Modify parameters according to user interactions in the GUI.
- Display simulation results in the GUI.
- Compute results that are static within the simulation.
- Decide which time step to visit.
- At every time step in the simulation, determine what data that is needed.
- If it is needed, then also determine whether an old value can be reused, if it can be interpolated from past and future time steps, or whether it is necessary to recompute it.
- Compute the necessary results.
- Analyse the data that has been written to the output files.

At a finer resolution, the parts which include computing depend not only on what kind of result that is sought, but also on what fidelity that is required. We propose that the functions for computing various results should consider a fidelity parameter, and that all functions are to be associated with classes that represents the various objects.

In order to allow for the time stepping scheme described in section 4.2.1, the time must be allowed to jump forth and back. For high fidelity computations, it may also be necessary to let the transmitting and receiving functions initiate computations of each other at time steps corresponding to the propagation time.

4.3.2. Object oriented view

In this section we will give a description of the simulator in terms of relationships between different parts of the hardware and physics that is modelled. This is probably the view that is most closely related to the implementation. It can be seen as an introduction to sections 4.3.3 to .4.3.8.

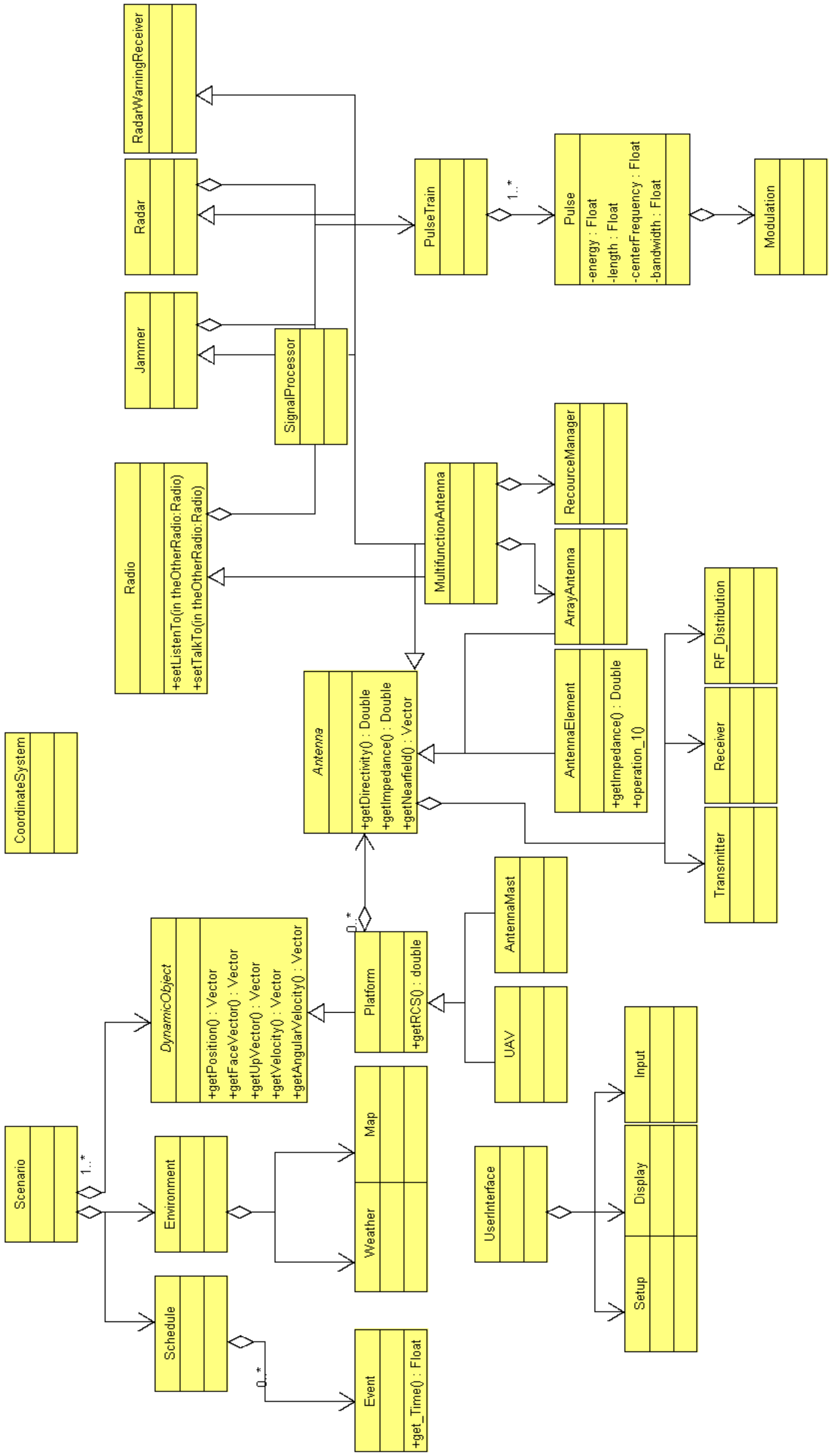

Figure 12 Class diagram representation of the simulator

A class diagram representation of the simulator is shown in figure 12. The aim is to illustrate relationships between different objects within the simulator. For instance, a 'MultifunctionAntenna' is an 'Antenna'. At the same time, it can also be a 'Radio' and a 'Jammer' etc. The 'MultifunctionAntenna' has an 'ArrayAntenna'.

We have listed a few methods for some of the classes. Naturally, the diagram is not complete. Most methods still remain to be declared, and most of the classes need to be specialised. It is probably a good idea for the programming team to start their work by constructing their own class diagram, and try to make it as complete as possible. It will probably be necessary to break it into several diagrams. All methods that are not intended as private should be declared with their parameter lists and return types. If any non-private variables are used, then they should also be declared at this stage.

If the class diagram is constructed in a good UML[9] tool, then it will be possible to automatically generate a code skeleton. It will also be possible to automatically update the class diagram if new classes are defined or if relationships are added or removed in the code.

4.3.3. Transmitter

The transmitter model can be used both in a stand-alone antenna, and as the transmitter in a multifunction antenna.

By a transmitter we mean a unit that generates a microwave-modulated signal. From a simulation aspect the model of a transmitter must at least have a method for answering the following question: How much power does it transmit in certain frequency bands?

The method should be able to handle that question at different fidelities. At the very lowest fidelity, it might give a dummy answer, but at higher fidelities the answer should be based on relevant computations that take into account the components that build up the transmitter, and naturally which antenna functions that are active and what their parameters are.

The output port could be modelled by the field strength in the outgoing wave in a transmission line and a frequency dependant S-parameter for modelling the impedance.

4.3.4. Receiver

In this section we describe how a receiver is modelled. It can be used both in a stand-alone antenna, and as the receiver in a multifunction antenna.

By a receiver we mean a unit that converts a microwave modulated signal into a base band signal, or in some cases even a digital signal. From a simulation aspect the model of a receiver must have a method for answering the following question: What are the signal power and noise power at the output? The receiver model should also be able to generate a time domain signal output.

The input port could be modelled by a frequency dependant S-parameter for modelling the impedance, and an ideal detector for measuring field strength in the incoming wave.

[9] For more information see http://www.rational.com/uml/resources/documentation/index.jsp

Typically, a receiver consists of filters, low noise amplifiers, local oscillators, mixers, and in some cases an A/D-converter. A high fidelity model will require accurate models for each component.

4.3.5. Signal processor

There are of course a variety of possible approaches of how to model a signal processor. As a minimum, we must be able to process simulation data in order to produce the desired output diagrams.

At the highest fidelity the signal processor might actually run the very same algorithms as the real signal processor it is trying to model.

The signal processor should use the output from the receiver as its main input. Some functions may also require input from other parts of the antenna. For instance, a radar processor needs to know when the signal was transmitted.

4.3.6. Resource manager

In this section we describe how the resources within the multifunction antenna are managed. At the most simple level of simulation we assume that there are no conflicts between different functions, therefore there is no need for resource management, but at a higher level of simulation the multifunction antenna must be able to resolve conflicts that arise when there is a demand of performing several functions simultaneously.

Two functions can in principle be performed simultaneously if the resources that are needed are not in conflict with each other. When there are resources available, it is mainly a matter of isolation.

The simulator should have some very simple means of resource management and scheduling. We propose that functions are to be performed in the order they are requested when there are resources available (a FIFO queue).

4.3.7. RF distribution

We propose that the RF distribution network between the transmitter/receiver and the antenna elements are to be modelled in a similar way as in BELSAS [15]. That is, the RF-generator, the antenna elements and components such as power splitters, power combiners, attenuators and delay circuits are described by S-parameters. After any modification to the parameters due to for example a change in the lobe steering, the combined S-parameters for the entire system are computed by the program before any further simulation is done.

4.3.8. Antenna elements and propagation

In this section we describe how the antenna elements, and an antenna array can be modelled. We want to be able to model both the directional and polarisation properties as well as the impedance properties. It should be possible to choose between free space propagation and some propagation model that take terrain and weather into account. We propose that the

Detvag package is used for this purpose A bit more elaborate description is given in section 5.2.4.

The directional properties of an antenna element can be described by assigning a gain for each direction, polarisation and frequency. It can be taken from either measurements, computations or some ideal function. The impedance of an antenna array can be described by an S-parameter matrix at each frequency, where the coupling between the elements is taken care of by the off diagonal elements.

In the receiving case, the incident field is the driving source. Therefore, the field strength in the outgoing wave in each transmission line should be set according to the incident field and the gain. Please observe that in an array the relative phase of the incident field must be considered.

In the transmitting case, the driving source is the transmitter described in section 4.3.3. We do not believe that it will be very beneficial to keep track of the propagation of the signal from every antenna element within an array. Rather, the array gain should be used to set the field strength in the transmitted wave.

An alternative to the method described above is to handle all antenna elements in a large S-parameter matrix where the coupling within the arrays is handled by the block diagonal, and the propagation between different antennas is handled by the off block diagonal. Unless the frequency resolution is finer than $\frac{1}{2t}$ where t is the largest propagation time (we certainly do not suggest to do it that way), it would still be necessary to keep track of the propagation time for each signal.

In either case it should be possible to assign a minimal number of properties, and let the simulator assume that the rest of the elements within the arrays are identical. The simulator should also be able to benefit from identical elements so that the same result is not computed several times.

4.3.9. User interface

It is most important that the user can review the parameters before actually starting the simulation and that there is a possibility to follow the progress of the simulation. It is also highly desirable to give the user help in setting up the scenario. Preferably, the user should also be able to interact with the simulation. For these reasons, a graphical user interface (GUI) is absolutely necessary.

It is an open question what the GUI should look like. It should probably have some tape recorder like buttons for controlling the flow of the simulation. Every input window should have an ‘apply’ button and a ‘cancel’ button. Action should only be taken when the ‘apply’ button is pressed.

The main display in a simulation is a geographic view of the scenario. The background of this display is a map. The same database that is used in the propagation model should also be used to generate the map. The simulation objects should be plotted using symbols of different shapes and colours.

It should be possible to open windows with detailed object information for review and modification either by clicking on the symbols or choosing from a menu. The user should be able to control both the movements, as well as the antenna parameters and the antenna activities from such windows.

For every type of analysis listed in section 4.1. there is a need for at least one type of graphical output, typically polar and rectangular charts are needed. It is important that they contain marks to assist in the interpretation.

4.4. Implementation aspects

4.4.1. Simulation language

We do not intend to prescribe which language to use, but the programming team should decide this themselves at an early stage. Some possible examples are listed below:

- Simulink/Matlab
- C, C++, Java
- Fortran 90
- Hybrids of the above

The main advantage of Matlab is that it is easy to build a GUI. It is also easy to use the built in math functions. The main drawback is the speed. It can also be rather difficult to adopt an object oriented approach.

C++ and Java are examples of object oriented languages. Since they are compiled, the code will run rather quickly. Standard packages for graphics can be used. For an experienced programmer, it should not be very difficult to build a GUI in such an environment.

Fortran 90 has very few advantages over C++ unless the programmer is experienced in Fortran but a novice in C.

It might be attractive to use some kind of hybrid, i.e. Matlab and C++. However, One would have to use the Matlab representation, which means that some of the difficulties to adopt an object oriented approach would still remain.

4.4.2. Code standards

Regardless of which language that is used, it is important to stick to some standard for naming, commenting and formatting the code, i.e. ISO 9001-3 or FEDEP. We do not believe that it has to be a universal standard. Any standard that the team can agree on is good enough. We suggest that the document 'Kodningsstandard för C och Visual C++' [16] is used in applicable parts.

There are also various standards/packages for allowing models to communicate with each other. A few examples are given:

- HLA
- COM
- DCOM
- Flames

The first three are probably not very attractive for the kind of technical simulation we are aiming at. Flames provide a GUI and a few example models. It is claimed that the Flames models can easily be extended or refined by adding C++ code.

4.4.3. Tools

We propose that a UML tool is used in the start-up phase for producing class diagrams and generating the code skeleton. A good UML tool can be synchronised with the actual code, and can thereby help with the documentation as well.

We also suggest that some kind of revision handling system is used, for example CVS[10].

4.4.4. Operating system, simulation platform

No special hardware requirements can been foreseen, other than that the simulations will result in rather heavy computing, at least at high fidelities. It is an advantage if the program can run in several different operating systems. It should at least be possible to have one UNIX version and one Windows version.

[10] For more information see http://www.cvshome.org/

5. Development of a system simulator

In this section we will describe the development of what we call simulator version 0.1. It is a highly simplified simulator. The main objective is to gain insight into the problems that can arise when building a system simulator, and possible solutions to those problems.

5.1. Description of the test scenario

The following scenario was chosen because it is a rather simple one. Only two functions of the multifunction antenna are demonstrated: communication and jamming.
The background is some international operation. A friendly helicopter has to pick up personnel within reach of a hostile fire control radar with air-defence artillery. Therefore we use two UAV:s for jamming the radar. The UAV:s also communicate with each other and with the base, but they are not exposed to any kind of jamming themselves.

5.2. Description of principles, algorithms and important objects

The program is written in Matlab 6 code. This allows for the use of structures and function handles, which in turn make it possible to adopt an object oriented approach.

There are two modes of operation, transmit and receive, the modelling of a received signal contains the same parts as the transmitting of a signal, with the addition of a communication model (or a radar model or what ever functionality is needed). The whole modelling chain for a signal is given in figure 13.

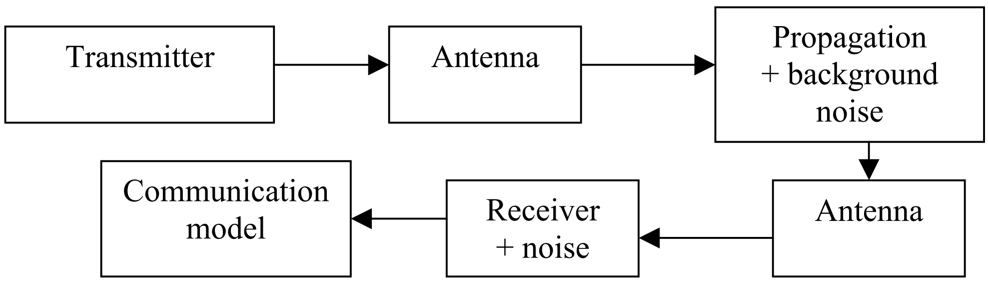

Figure 13 The modelling chain for a signal.

For most of the simulation parts it is possible to assign one frequency dependent factor representing the impact on the signal, and then at the end multiply those factors. In addition noise has to be handled in parallel to the signals, which is done in three stages. Noise is added as background noise, receiver noise and interfering transmitters.

There is no reason to update (recalculate) all the different parts of the simulation each time a signal is transmitted through the chain. We assume that the actions of the transmitter and receiver are constant, i.e. we never update those. The action of the antennas and propagation on the other hand typically needs updating when the objects have moved too much from the position in the previous calculation.

5.2.1. Object and antenna representation

We have chosen to represent each object such as UAV:s, communication masts, radar units etc. by cells in a global array called 'obj'.
Each cell is a structure that contains fields that can be translated to position and orientation of the object at any given simulation time.
Each cell also specifies which function that is to be used for generating graphics.

Each object can have up to three antennas. They are declared within the 'obj' cell array. But the antennas themselves are represented by another global cell array called 'antenna'.

Each cell within 'antenna' contains a field with the name 'gain' which is a handle to the function that should be used to compute the gain for the antenna. It is possible to choose between 'array_gain', and 'aperture_directivity'. The input to the gain functions are the transmitting or receiving signal structure (se section 5.2.2) and the directions and frequencies for which gain is to be computed. The signal structure is needed because we consider gain to be a property of it, rather than a property of the antenna. The size of the sub array that is assigned to a certain task, and the electronic steering are important factors for the gain. They are stored in the signal structure.

If 'array_gain' is chosen, then the antenna is assumed to be a rectangular group antenna with $n_x \times n_y$ identical elements. A function for computing the element pattern must be specified. Only 'meas_gain' is implemented at the moment. Any element spacing is valid. 'meas_gain' computes the element gain by interpolation in a table of frequencies and angles.

The 'array_gain' function first computes an array factor A as a sum of complex weight factors with a phase shift according to the difference in path lengths for the individual elements in the desired directions. Then the pseudo gain $\tilde{G}$ is computed by taking the absolute square of A and multiplying with the element gain. The gain is then given by equation

$$G = 4\pi \frac{\tilde{G}}{\oiint \tilde{G} d\Omega} \qquad (2)$$

The surface angular integral is computed by a numerical method using $n_\theta \times n_\phi$ angles
The complex weight factors are determined by the desired lobe steering as specified for the signal.

The antenna array surface is always in the xy-plane in the local coordinate system.
The local coordinate system for the antenna is obtained by applying a transformation matrix to the local coordinate system of the owner object. It is possible to use yet another coordinate system for specifying the element diagram.

If 'aperture_directivity' is specified, then the gain from an aperture with a given field distribution in an infinite ground plane is asumed. We have implemented the case of a circular aperture with a uniform field distribution [17]. A parabolic reflector antenna is not equivalent to this kind of ideal aperture but we use the approximation anyway because it is a simple one. The approximation is only meaningful if the diameter of the reflector is at least a couple of wavelengths.

5.2.2. Signal representation

The electromagnetic spectrum is treated as a number of non-overlapping frequency bands characterised by start and stop frequencies. A broadband signal may occupy several bands, and the power density can be different in different bands, but it is constant within each band. The frequency bands are defined in the global variable ‘freq’. In the present version of the simulator all computations are done at the centre frequency within each band.

The transmission of signals is controlled by the global cell array called ‘signal’. Each cell represents a transmitting antenna function. The fields ‘obj’, ‘obj_antenna’ declare which object and which antenna on that object that is used for transmitting the signal. The field ‘target_obj’ is used by ‘array_gain’ in order to set the direction of the main lobe.

The transmission is active between the times given in the ‘start’ and ‘stop’ fields. The energy is spread over the frequency bands listed in the ‘freq’ field with power densities according to the field ‘power’.

It is not necessary to use all elements in an array antenna for a certain antenna function. The sub array that is used is defined by the field ‘array’ which contains four numbers [x_0, x_N, y_0, y_N]. In this way rectangular sub arrays with dimension (x_N- x_0)×(y_N- y_0) can be defined.

The receiving of signals is controlled by the global cell array called ‘ear’. This is not a very good name, but it would take some work to change it into something better. The structure of ‘ear’ is almost identical to that of ‘signal’. The main difference is the lack of the field ‘power’ in ‘ear’.

5.2.3. Transmitter and receiver model

The cell arrays defined for transmitting and receiving signals that were described in the previous section represents signals leaving or entering the antenna. In addition to this, models for some of the transmitting and receiving functions are treated. Tx/Rx functions that might be necessary to consider and that will affect the system performance include: frequency conversion (up/down), noise treatment, linearity, dynamic range and gain/loss. At this stage simplified models have been introduced to account for the effects of some of these parameters. A/D conversion and digital signal processing is not considered.

The basic idea is to use the signals defined earlier and apply the selected model, the function ‘trans_rec’ use these as input and produce an output representing the transmitted or received signal. The signals that are input to the function are defined as having a power density in a number of frequency bands. These bands are taken as the operating bands of the transmitter or receiver. The model is then defined by associating a gain/loss (G), noise figure (Nf), input noise power density (n) and output frequency band for each input frequency band. Concerning the linearity each band is also associated with an input power 1dB compression point (P1dB). The model is represented using a 6 column wide matrix or as a cell array with separate fields for each property.

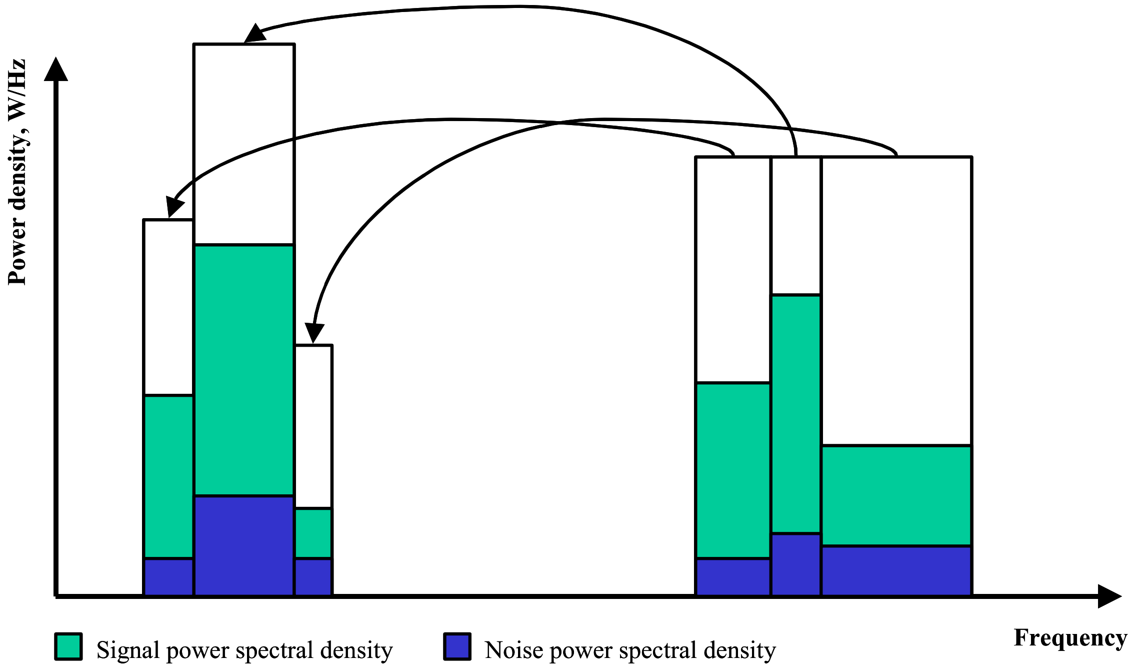

Figure 14 Frequency conversion scheme for a receiver.

The gain/loss is given in scalar units and represents the entire transmitter or receiver gain/loss. With the input noise power spectral density (PSD), defined as equally distributed over the frequency band, the input noise power (PSD*bandwidth) and signal to noise ratio (SNR) can be achieved. By defining a noise figure (Nf) for each band, the signal to noise ratio at the output and output noise power can also be calculated. Additional noise representing for example jammers is easily included in this model.
Having the possibility of defining different output frequency bands for each input band allows for a reasonable amount of different receiver types to be modelled. Wide instantaneous bandwidth (all output bands different), hopping frequency using image rejection (all output bands the same.) for example. The linearity parameter, P1dB, works for both the receiver and transmitter case but deals only with the linearity of the basic harmonic frequency. The use of input third order intercept point (IIP3) instead admit calculation of for example receiver dynamic range which is mostly limited by this two tone intermodulation distortion.
Improvements for the models at this stage include allowing a nonuniform signal and noise power distribution for each frequency band. A frequency conversion spurious control is also needed to ensure the integrity of the converted signals. Establish an interface to other parts of the transmitter and receiver circuitry. In more advanced modelling of the transmitter and receiver chains, the above described block representation needs to be divided into a circuit level representation to allow for more flexible transmitter and receiver architectures. The circuits could also be defined using simulated data, measured data or analytical models.

5.2.4. Propagation model

The simulation needs to know the resulting electromagnetic waves at objects, when one of them is transmitting. An approximation is obtained using the software Detvag[11]. It is a package containing several methods that can complement or replace each other, important parts being a knife edge diffraction code and a general theory of diffraction (GTD) code. The range of frequencies which it is covering is approximately 10 kHz-10 GHz. Detvag can use

[11] Detvag is a registered trademark of the Swedish Defence Research Agency. It is a Swedish acronym for ‘deterministic wave propagation’, and was written during the eighties and nineties.

information from maps, such as terrain-height profile and vegetation, but it is a two-dimensional program, disregarding multi-path effects.

Exactly which code-combination that will be used is undecided. Ideally it should vary according to the set up of the simulation. The information extracted from Detvag is the attenuation between relevant objects for relevant frequencies, but no phase information. It is even assumed that the propagation is instantaneous.

5.2.5. Communication model

In the implemented scenario there is no jammer present and hence there is no point of using Frequency Hopping (FH). In a realistic scenario where the UAV functions as a jammer it is likely that it will itself be exposed to jamming and in this case FH could be used. FH has consequently not been implemented at this stage.

The main parts in the modeling of the receiver are the demodulator and the decoder. Before the demodulator there is a signal processing block, which symbolizes all pre-processing that has to be done to obtain the separated signal (S) and noise (N) in the receiver over a given bandwidth W, see figure 15. Obviously the receiver is simplified but it suits our purposes.

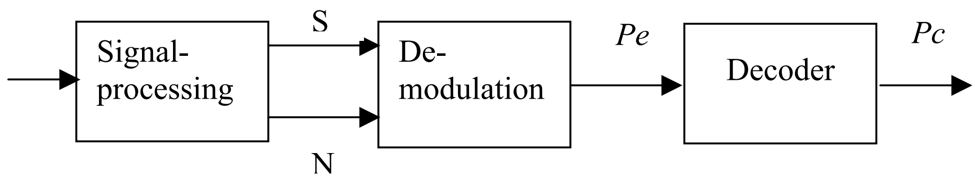

Figure 15 Block diagram for simplified receiver

Assuming that we are frequency-hopping fast enough or that an interleaver of sufficient depth is used it is reasonable to consider the channel to be additive white Gaussian noise (AWGN).

The modulation scheme is chosen to be Quadrature Phase Shift Keying (QPSK). It is a relatively robust scheme with a good spectral efficiency. The bit error rate of a QPSK scheme on an AWGN channel is given by (3).

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \qquad (3)$$

where E_b/N_0:

$$\frac{E_b}{N_0} = \frac{S \cdot T_b}{N/W} = \frac{S/R_b}{N/W} = \frac{S}{N} \cdot \frac{W}{R_b} \qquad (4)$$

and E_b is the energy per bit, N_0 is the power spectral density of the AWGN, S is the signal power, N is the noise power, T_b is the bit time, R_b is the information bit rate and W is the signal bandwidth.

The bit error rate after a block code (n,k,t) on an AWGN channel can be approximated by (5), which is a good approximation for high SNR and slightly worse for low SNR.

$$Pc < \sum_{i=t+1}^{n} \frac{i+t}{n} \binom{n}{i} p^i (1-p)^{n-i} \quad (5)$$

As error correcting code BCH (63,51,2) is chosen.

5.3. Input

The main user input is done by modifying the code in the start-up files. Some tuning of the parameters can be performed from within the graphical user interface, but it is first and foremost a way to check that the input files are correct.

5.3.1. Scenario setup

The procedures ‘set_obj’, and ‘set_antenna’ are called during the program start-up. Those procedures modify the global cell arrays ‘obj’ and ‘antenna’.

New objects and antennas are introduced by adding new cells in one of those variables. The simulator can handle up to 6 objects and 3 antennas per object. The restriction has been introduced for GUI-purposes only.

The motion of an object is controlled by three fields in the cell containing correlated vectors (matrices), ‘t’, ‘r’ and ‘n’. At the times listed in ‘t’ the position is given by ‘r’ and the local coordinate system is given by the unit vectors in ‘n’. At times not listed in ‘t’ the position and orientation is computed by spline interpolation. After the interpolation unit vectors are normalised to length one.

Which fields to update, and which to normalise are controlled by the ‘update’ and ‘norm’ fields that are also contained in the ‘obj’ cell. In this way it is easy to define new kinds of objects that may require more parameters. A stationary object can have empty ‘update’ and ‘norm’ fields.
‘set_antenna’ first defines three antennas per object, but disables them by setting the ‘skip’ field. This step is taken in order to prepare for user input from the GUI. Next the antennas for the default scenario are configured.

For each antenna to use, the ‘skip’ field is set to zero.
The ‘nx’, ‘ny’, ‘dx’ and ‘dy’ fields are set to the number of antenna elements and the spacing in each direction of the antenna array. For a single element antenna ‘nx’ and ‘ny’ should be one. A handle to a function for computing the gain is stored in the ‘gain’ field.

If ‘array_gain’ is chosen then a handle to the element gain is stored in ‘el_gain’ and relevant parameters for the element gain function are defined.

If ‘aperture_directivity’ is chosen, then for instance the shape, the field distribution and dimensions of the aperture are defined. At the present it is only possible to choose a circular aperture on groundplane with uniform fields in which case the radius is given.

Once the program has started, the user can enable or disable antennas, change the number of elements and the spacing of antenna arrays from within the GUI. It is also possible to change the orientation relative to the platform.

5.3.2. Signal setup

Simply defining the movements and the antennas is not enough. It is also necessary to define the signal activities. To do this in a rigorous way would require a lot of work. Imagine for instance a communication link with alternating talk and listen using advanced modulation schemes and hop frequency.

We choose to ignore the frequency hopping and silent periods. A transmission continuously uses its allotted frequency bands from the start to the stop time as defined in the 'start' and 'stop' fields. It is possible to group the start and stop times close together and make sure that computations are performed in that time slot, but we believe that the possible data rate during a length of time (or whatever entity that is under study) is more interesting than an instantaneous value from a very specific scenario.

The subroutine 'set_signal' is used for setting up a default combination of transmitting and receiving antenna functions in the 'signal' and 'ear' structures.
The fields to set are 'obj', 'obj_antenna', 'target_obj', 'start', 'stop', 'freq', 'array', and 'power' in case it is a transmission.
The 'antenna' structure is also updated with a link to the current 'signal' or 'ear'.

Further transmissions and receivings can be added from within the GUI.

5.4. Output

The code is not ready for practical use yet. At the time when this document is written, only the debugging output has been implemented.

5.4.1. Debugging output

In order to debug and to verify various parts of the code a polar indicator has been implemented.

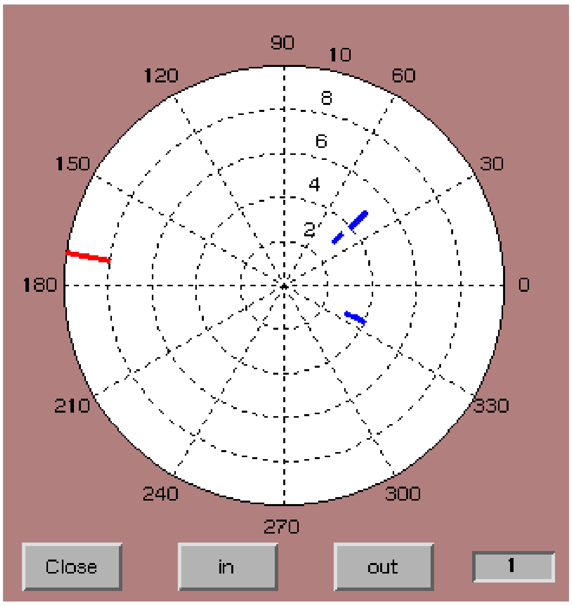

Figure 16 Incoming signals at an object. The angle is the direction of the transmitter. The radial distance represents the frequency, and the colour represents the intensity of the signal.

It is possible to plot either incoming signals at an object, or signals that are transmitted from an object.
The intensity of an incoming signal is computed by multiplying the output power, the transmitter gain for the relevant angle, and the propagation factor. In free space the propagation factor is simply $\frac{1}{4\pi R^2}$ where R is the distance between the transmitting and the receiving object. It is more complex in a realistic environment, see section 5.2.4 for a further discussion.

5.4.2. Signal to noise ratio

This part is not implemented yet, but the intention is to be able to present signal to noise ratios (SNR) and jammer to signal ratios (JSR) in a way that resembles a graph paper plotter. There should also be some markers to ease the interpretation of the degradation of the function under study.

5.4.3. Bit error rate

In a communication link, the estimated bit error rate (BER) is perhaps more easy to grasp than SNR. Once the power and the SNR are computed and the modulation scheme and data rate are chosen, an estimation of the BER can be obtained from the formulas in section 5.2.5. The BER will be presented in the same way as the SNR.

5.5. Assumptions and simplifications

Some of the assumptions and simplifications that have been introduced in order to build the simulator are given in the list below.

- Polarisation and impedance mismatch are not considered in the computations.
- The near-field environment is neglected in gain-calculations.
- Losses are neglected in the array gain computations
- Reflector antennas are approximated by ideal aperture antennas.
- A measured gain is interpolated from only two spherical cuts at each frequency.
- A frequency band is characterised by the centre frequency only.
- Multi-paths as well as other details and minor terrain features are not considered in propagation, as well as the time for propagation.
- Exact time-scheduling of signals is disregarded.
- No advanced signal processing is possible.
- A very simple noise-model is used, both as regarding the representation and generation of it.
- Very simple models of the transmitter and receiver are used.
- The scattering is based on a constant scalar radar cross section.
- Elements in an array are assumed to be identical.

5.6. Graphical user interface

The program is still under development, and even though it is clear how the simulations will be done, the details of the interface has not been worked out. The idea is not to create a user interface that can handle everything, but instead let the user to set up the simulation through variables in Matlab, i.e. to modify the m-files. The graphical part is mainly intended for presenting the simulation and its results, and some basic tuning and commands such as starting and stopping the simulation. The reason we do not implement the input part graphically is that it is not trivial to create such a graphical interface that is easy to use, and we would in any case not have the time at our disposal to be able to implement the whole set up.

The main window in figure 17 below, shows the map and the objects location on it. In addition there is for each object a note containing some basic information. Additional information can be viewed in separate windows (example below), reachable by either the main windows menu, or a context menu shown when right-clicking on the note corresponding to the object in question.

In the upper part of the main window there are buttons starting and stopping the simulation as well as a clock showing the number of 1/100 seconds in the scenario timeline that has past since the start of the scenario.

An important part of the graphical information will be the windows showing the results of the simulation, an example being the time evolution of the bit error rate for some communication between to objects. Such windows have not yet been implemented.

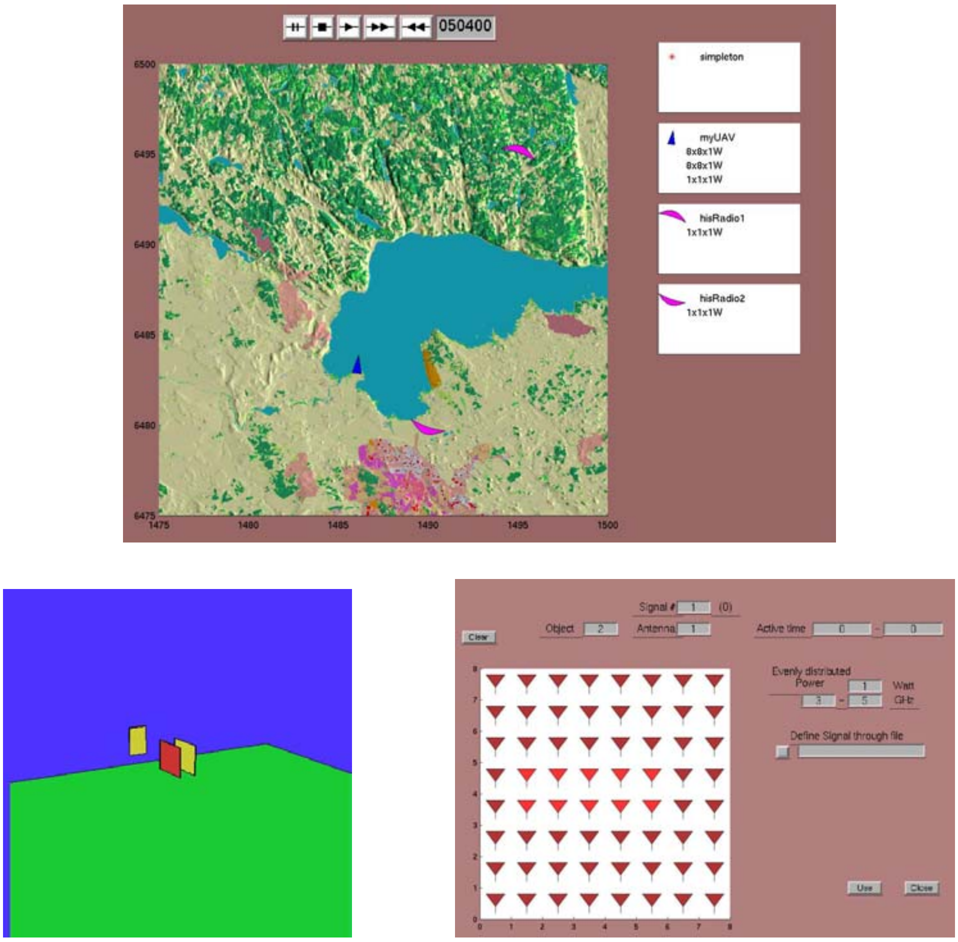

Figure 17 *The main window, a window showing the locations and directions of an objects arrays, and a window showing information regarding a specific signal, such as which elements in the array that are transmitting it.*

6. Conclusions

In this report a discussion regarding the benefits, limitations, technical implications and use of microwave based multifunction systems has been presented using different perspectives. A number of advantages, especially for small platforms, can be identified. The advantages can either be put into technical (increased performance etc.), tactical/operational (increased number of functions, increased survivability etc.) or economical (lower total cost) terms. The disadvantages identified so far are generally speaking a matter of prioritizing the functions desired, i.e. technical compromises as well as resource allocation compromises between different functionalities.

Furthermore, general design principles for the development of a simulation tool for a multifunction system have been compiled. This covers a discussion of the objectives of simulation, the structure of the model and implementation aspects.

Finally, a description of v0.1 of the simulation tool developed is given. The tool is currently implemented in Matlab 6 and is capable of handling a test scenario involving jamming and communication functions. The depth of the simulation is today very limited and further efforts will be put into expanding both scenario handling and model accuracy. However, the objective of v0.1 was not to build a fully equipped simulation tool, but rather to gain experience and also to give an indication of the applicability of such a tool to more system-, or mission-oriented users.

7. Further work

The project will, in the year to follow, start the implementation of the simulation tool according to the design principles that have been compiled. The efforts will be focused at coding and validation of the simulation core, but a number of modules are also to be developed and validated. During this work, the assumptions and simplifications discussed in chapter 5.5 will be considered and treated in a structured manner. The work regarding design principles and technical concept presented in this report will also be continuously revised and updated, if necessary.

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